Aeroacoustic Prediction and Noise Reduction
from aircraft applications

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Outline

- Which phenomena does Aeroacoustics deal with?
- Aero sound source at aircraft
- Theoretical foundations - origin of aerodynamic sound generation
- Simulation of turbulence related sound
- Numerical simulation - examples
- Reduction of aerodynamic noise
- Summary & perspective

Aeroacoustic phenomena of interest for a/c

- sound generated aerodynamically
  - directly, inside the fluid & related surface pressures
    e.g. jet noise, rotor noise, airframe noise, cavity tones …
  - indirectly through flow induced vibration of surfaces
    e.g. cabin noise, acoustic fatigue problems …

- sound propagating through flow fields
  - e.g. refraction of sound at shear- / temperature layers,
    scattering at turbulence …

Sources of exterior noise at aircraft

Take off:

► **engine**
* jet
* fan tonal (+ broadband) / propellers
* compressor

Approach:

► **engine**
* jet
* fan broadband / propellers
* combustion

► **airframe**
* high lift devices
* jet-flap interaction
* landing gear & flap interaction
* spoiler & spoiler induced flow

Sources of interior noise at aircraft

- **exterior excitation:**

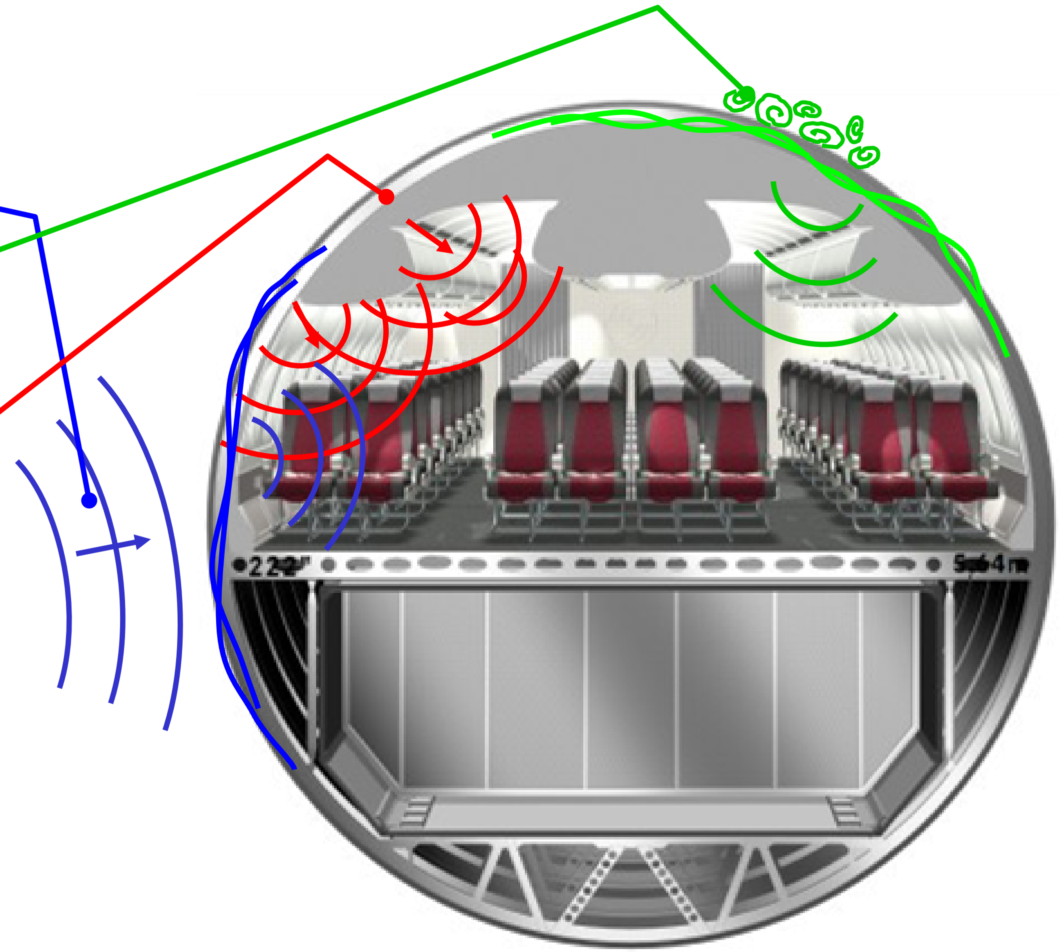
airborne engine noise

fuselage boundary layer

- **interior excitation:**

air system

(hydraulic system)



Simulation of propeller noise

Complete A/C radiation: wave eqn.

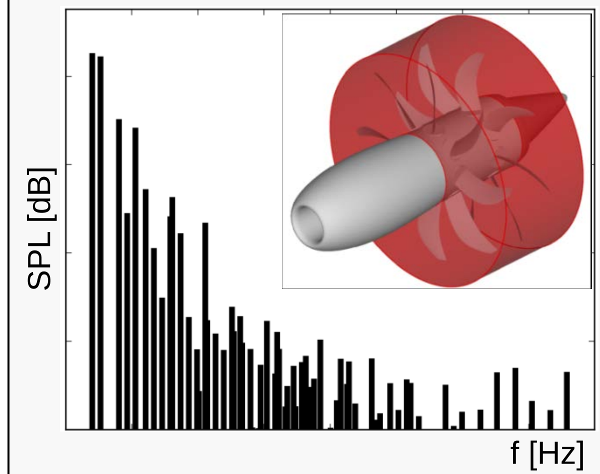
Source → **Interface model** → **Wave equation**

URANS/CAA
analyt.models

FW-H APSIM+
Ray tracer SHADOW
Fast Multipole BEM

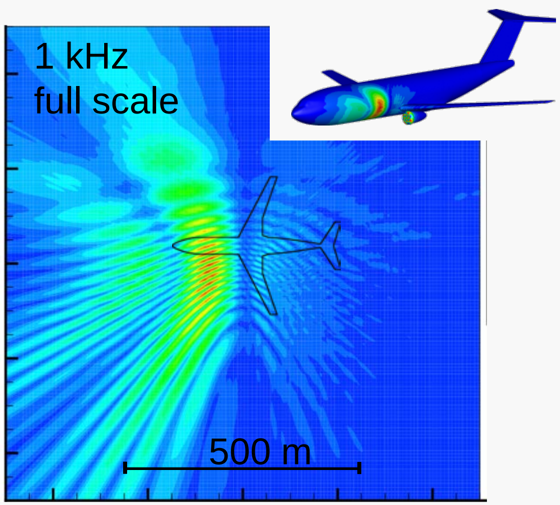
⇒ computation of acoustic installation + a/c farfield

Open rotor noise



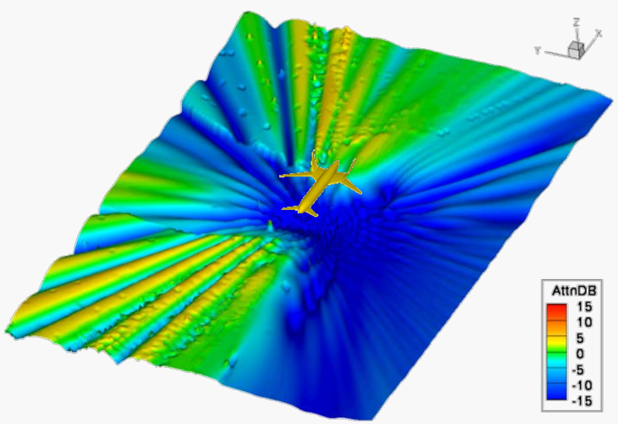
Flow: TAU/ sound: APSIM+

Acoustic a/c installation fan



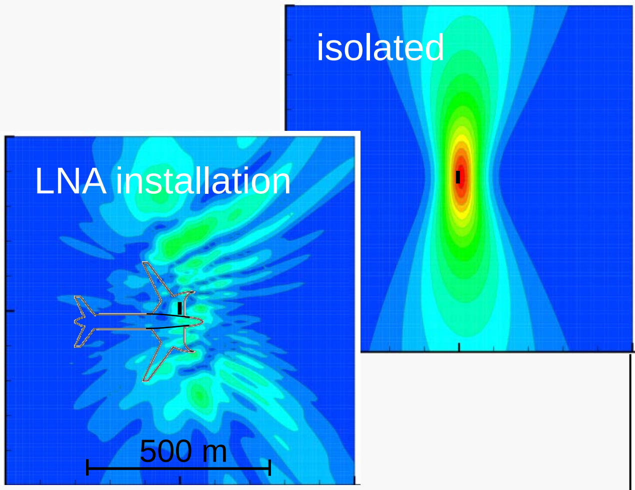
source: anal. (RRD)
sound: FM- BEM

Ultra fast installation estimation



source: directed point source
noise: SHADOW

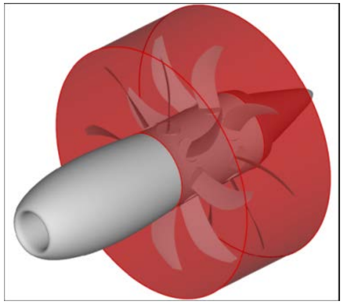
Acoustic a/c installation OR

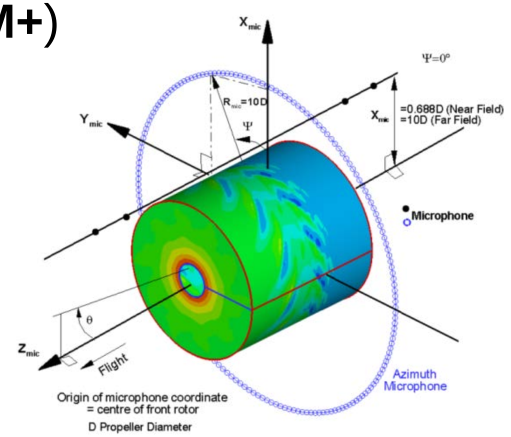


source: TAU fed analytical model
noise: FM-BEM

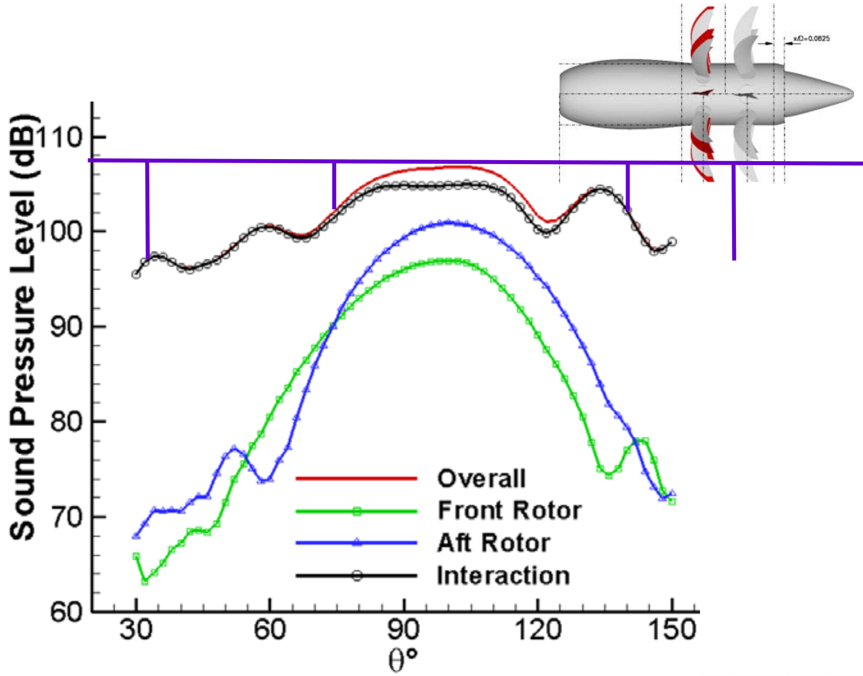
Tone Noise prediction of counter rotating open rotors

CFD (**TAU**) + Ffowcs-Williams & Hawkings solver (**APSIM+**)

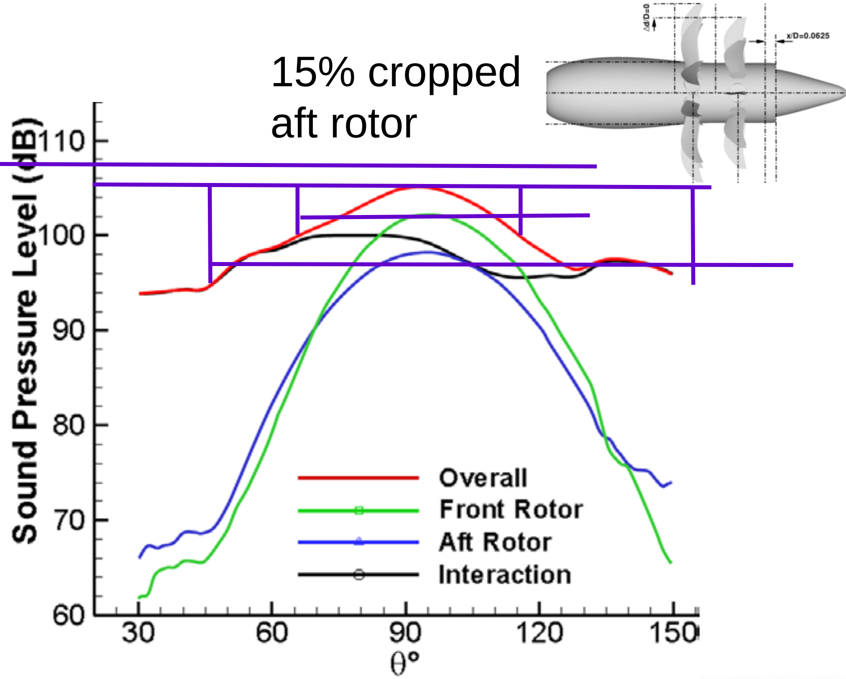




Farfield (10D) noise prediction
10x8 CROR M=0.2, take-off
comparison of 2 ORs same thrust



15% cropped
aft rotor

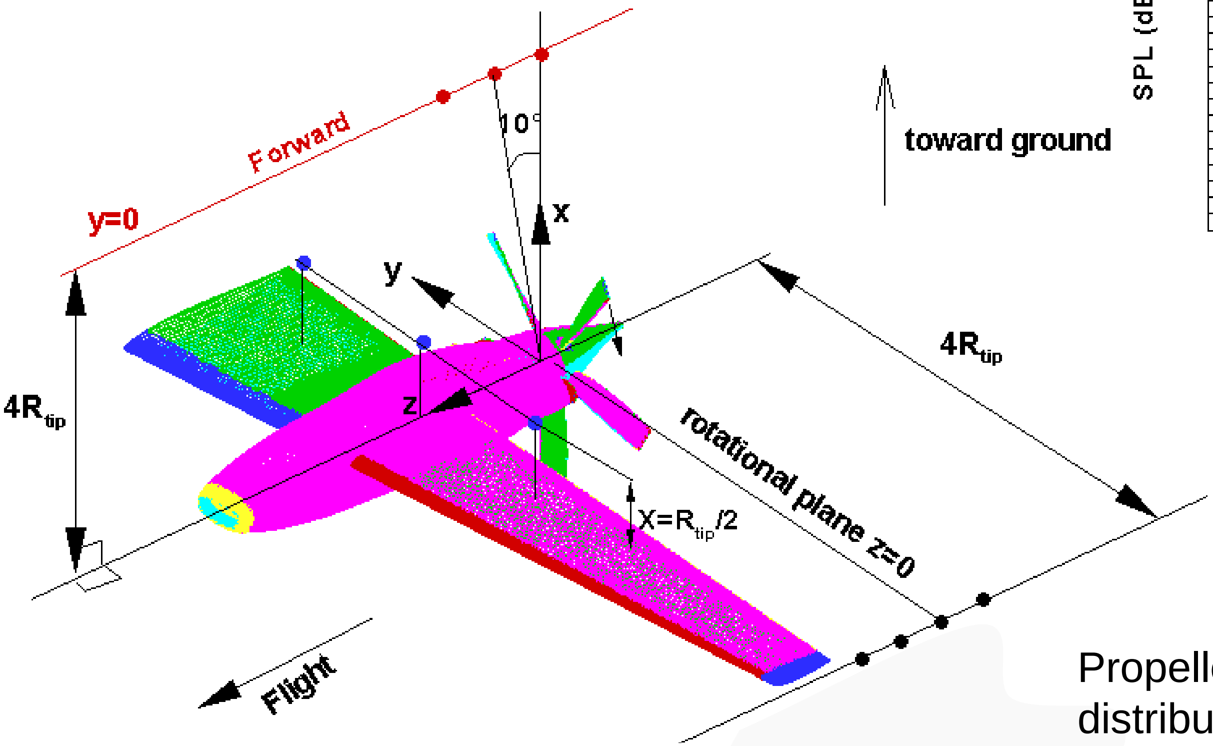


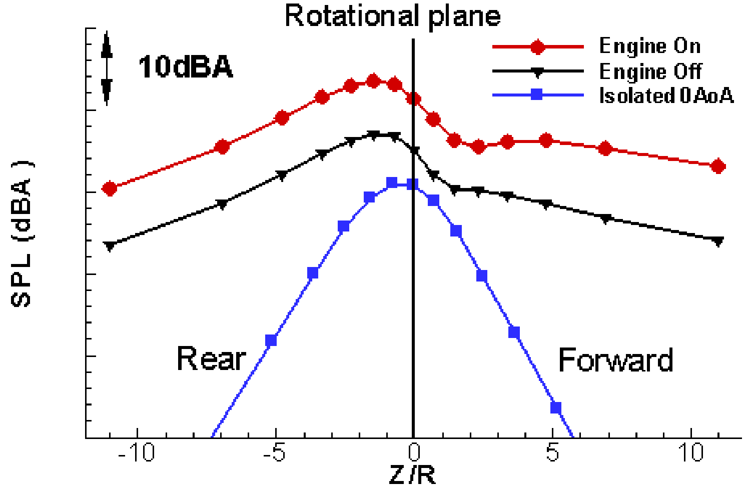
Installed propeller noise

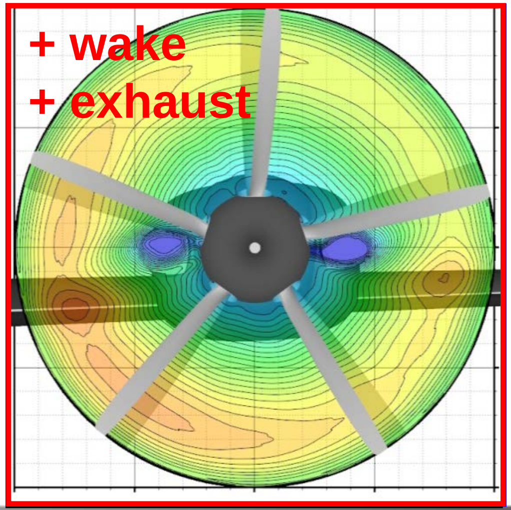
sound radiation of installed pusher propeller (Piaggio), Take-off

$$p'(\boldsymbol{x},t) = \frac{1}{4\pi r_0 a_\infty} \int_{\partial V_B} \frac{\dot{f}_r}{|1-M_r|^2} + \frac{f_r \dot{M}_r}{|1-M_r|^3} dS(\boldsymbol{\eta})$$

$$f_r := \boldsymbol{e}_{r_0} \cdot ([p\boldsymbol{I} - \boldsymbol{\tau}]\boldsymbol{n})$$







Propeller load distribution

Yin, Stürmer, Aversano 2009, AIAA 2009-3332

Installed propeller noise

sound radiation of installed pusher propeller (Piaggio), Take-off

$$p'(\boldsymbol{x},t) = \frac{1}{4\pi r_0 a_\infty} \int_{\partial V_B} \frac{\dot{f}_r}{|1-M_r|^2} + \frac{f_r \dot{M}_r}{|1-M_r|^3} dS(\boldsymbol{\eta})$$

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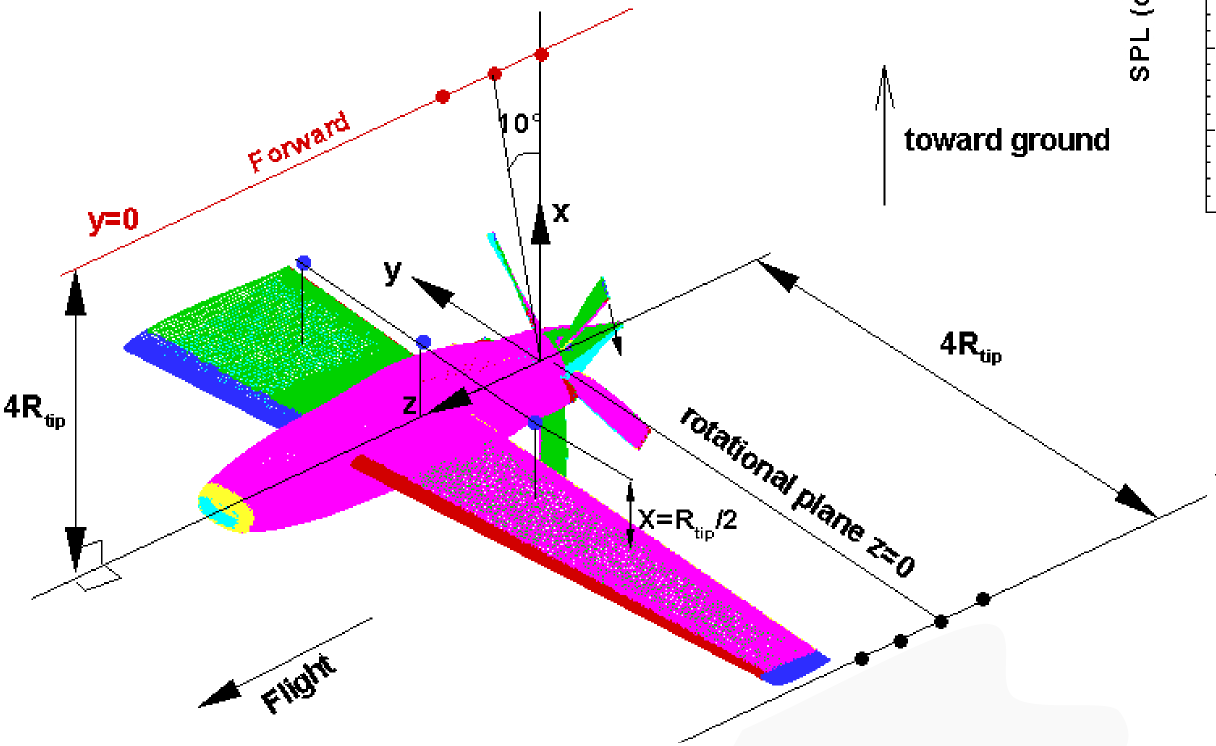
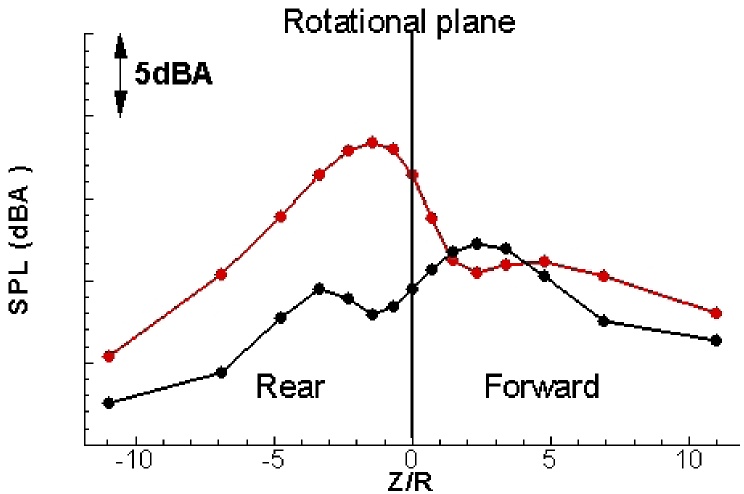
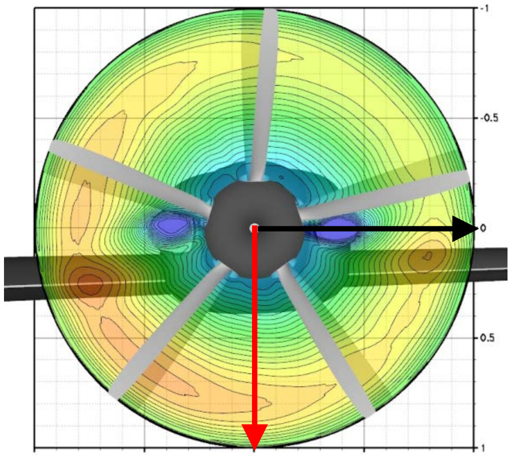


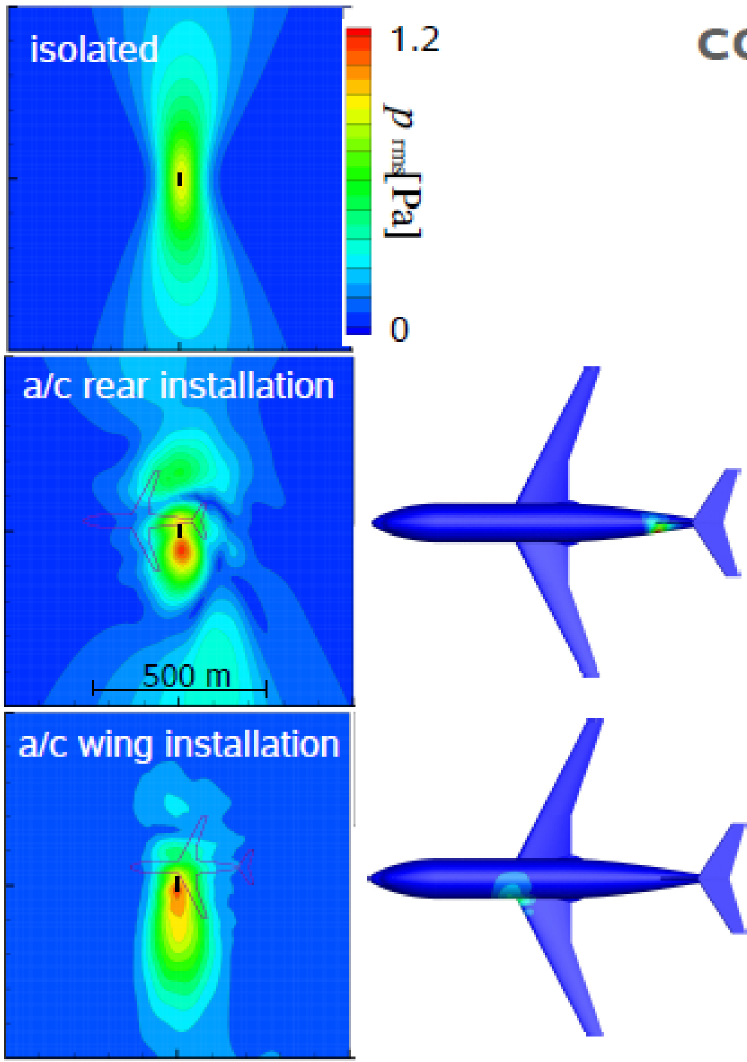




Yin, Stürmer, Aversano 2009, AIAA 2009-3332

CROR acoustic installation effects configuration studies

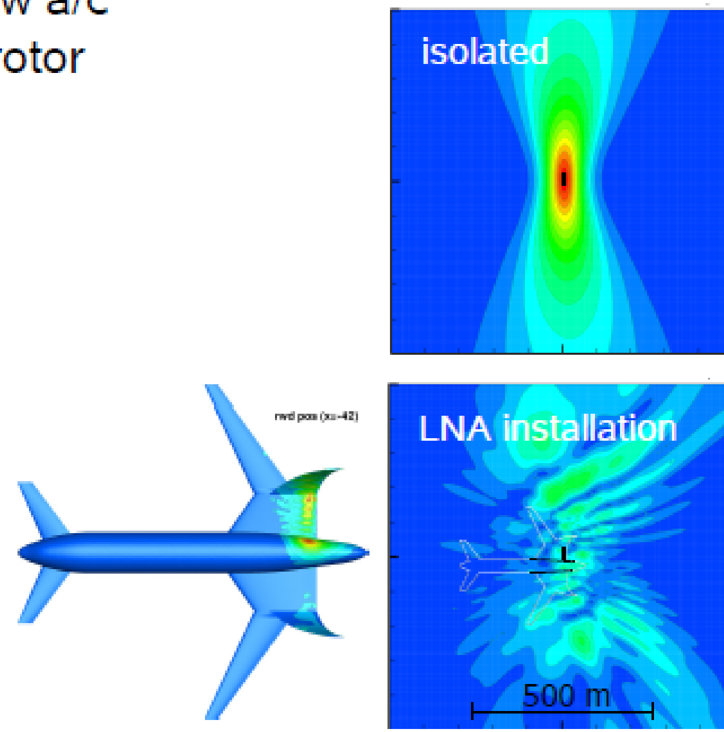
conventional a/c



3 dB **increase**

Footprints of loading noise 120m below a/c for BPF of front rotor

DLR Lna/c

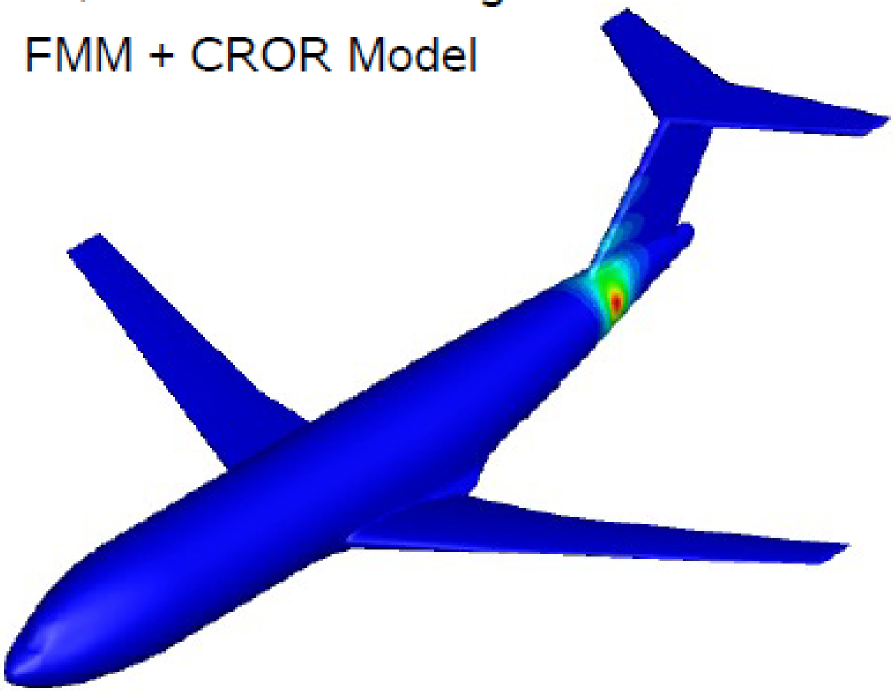


10-12 dB **reduction**

Source: uRANS
Sound: FMM BEM

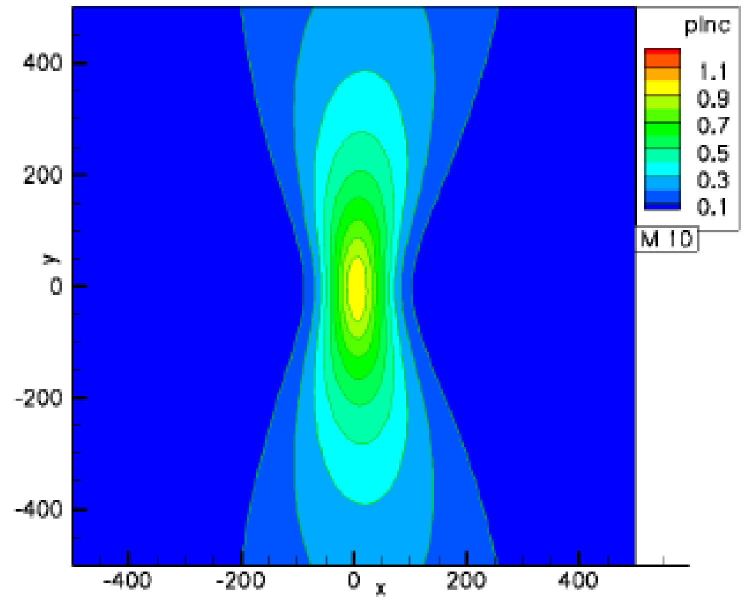
F6OR Configuration
Front rotor installation effect

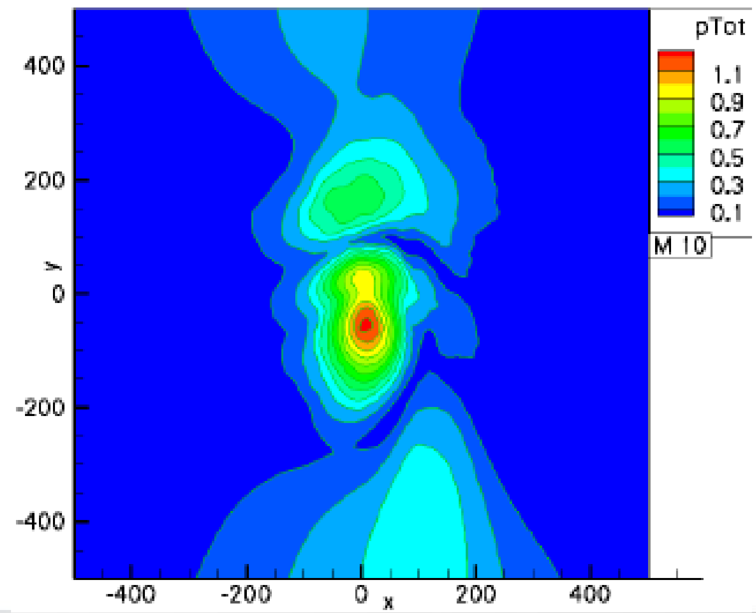
- 50,000 Surface Triangles
- FMM + CROR Model



B_f=10

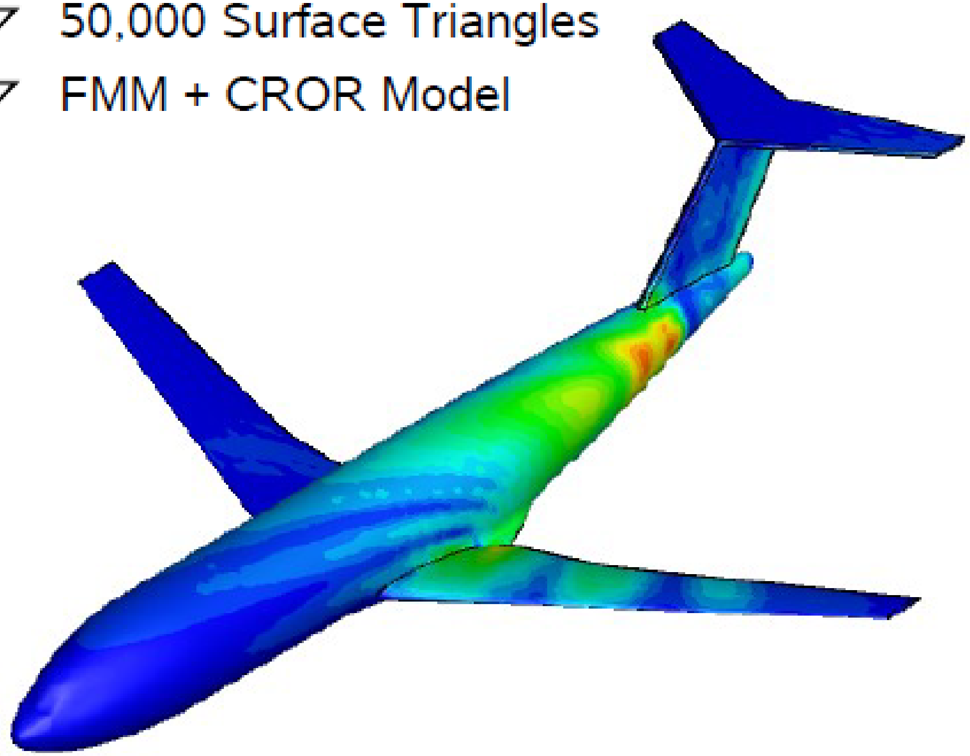
Source: uRANS
Sound: FMM BEM



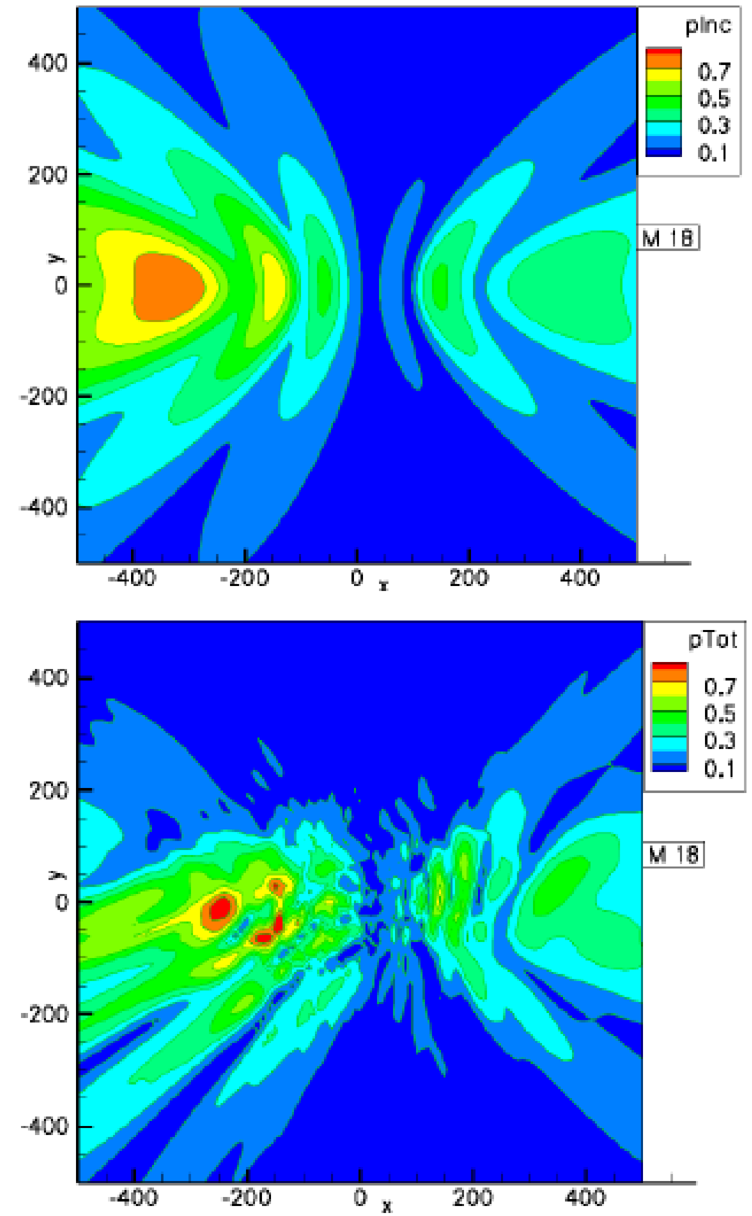


F6OR Configuration
Interaction Harmonics

- 50,000 Surface Triangles
- FMM + CROR Model



$B_f + B_a = 18$

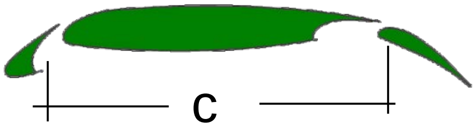


Source: uRANS
Sound: FMM BEM

Simulation of turbulence related sound

The challenge of predicting turbulence related sources

Prediction of the flow noise of a wing using scale resolving flow simulation (e.g. DES – Detached Eddy Simulation)



Typical mesh resolution for wing section:

$30 \cdot 10^6 \mathrel{\widehat{=}} \Delta b \sim 3\%$ c spanwise (experience e.g. TU-B)

$b \sim 5 \cdot c \;\Rightarrow\; b \sim 5 \cdot 33 \cdot 30 \cdot 10^6 = 5 \cdot 10^9$ cells

$\Rightarrow$ ~ 10 billion cells for appropriate description of sound sources at complex 3D wing

For model Reynolds number 1:10

$\Rightarrow$ ~ trillions of cells for wing at original Reynolds number !

$\Rightarrow$ excessive computation cost for turbulence **simulating** methods

– non-appropriate for design tasks

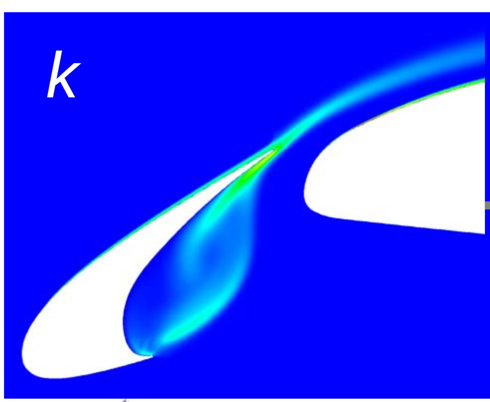
+ useful for clarifying source mechanisms, validation data

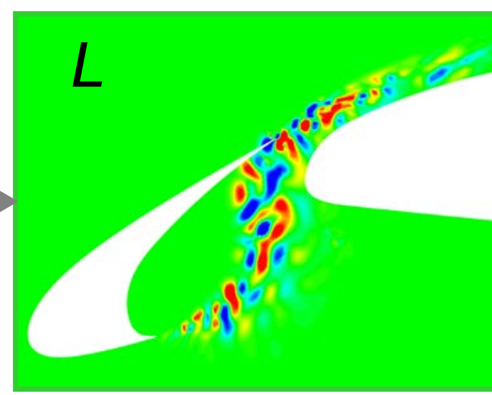
CAA Simulation concept for turbulence related sound

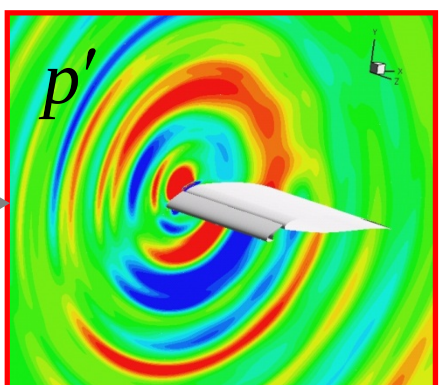
CFD RANS — Time averaged flow $\overline{\boldsymbol{v}}, \overline{\rho}, \overline{p}$ → **CAA APE** — p' → **Sound Field**

CFD RANS — Turbulence-statistics k, ω → **Stochastic Sound Sources (RPM)**

Stochastic Sound Sources (RPM) — Source $\boldsymbol{L} = -\overline{\boldsymbol{\omega}} \times \boldsymbol{v}^t - \boldsymbol{\omega}^t \times \overline{\boldsymbol{v}}$ → **CAA APE**



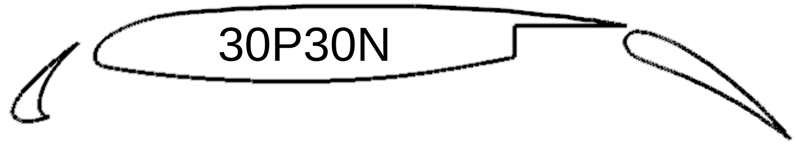




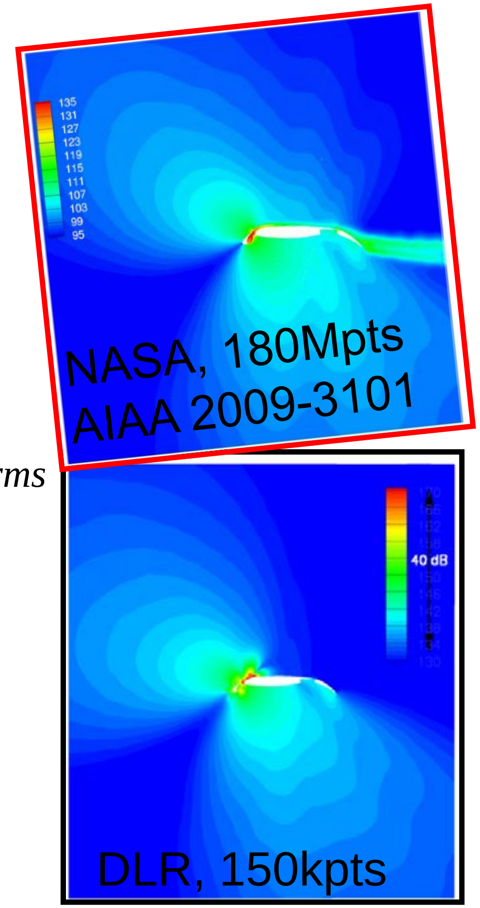
Numerical Simulation – examples

Airframe noise of high lift airfoil 30P30N

- Comparison of stochastic approach (PIANO) with other groups

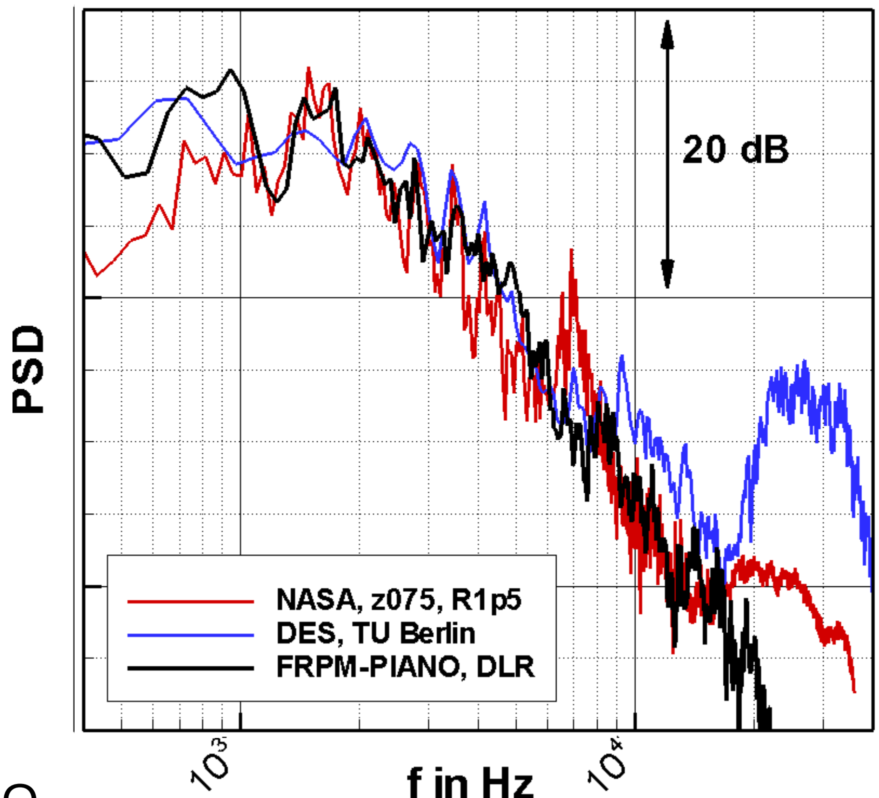


p_{rms}

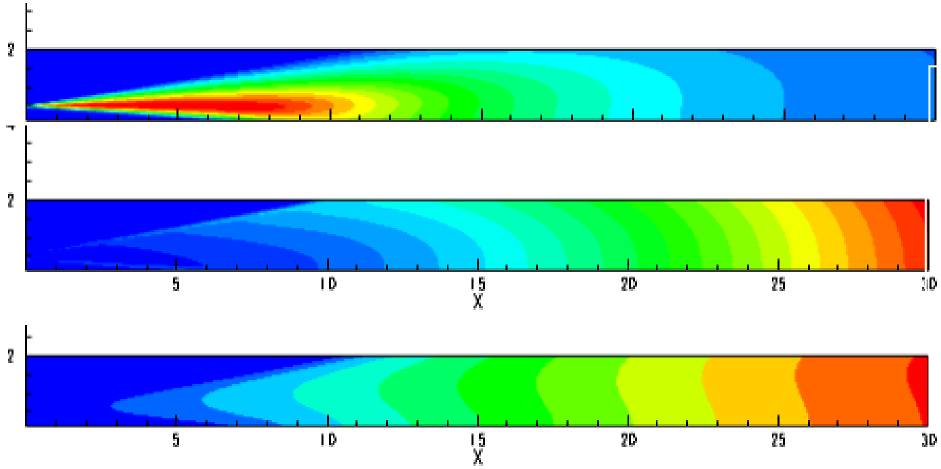


flow: TAU
sound: PIANO

290° w.r.t. flow



Jet noise prediction

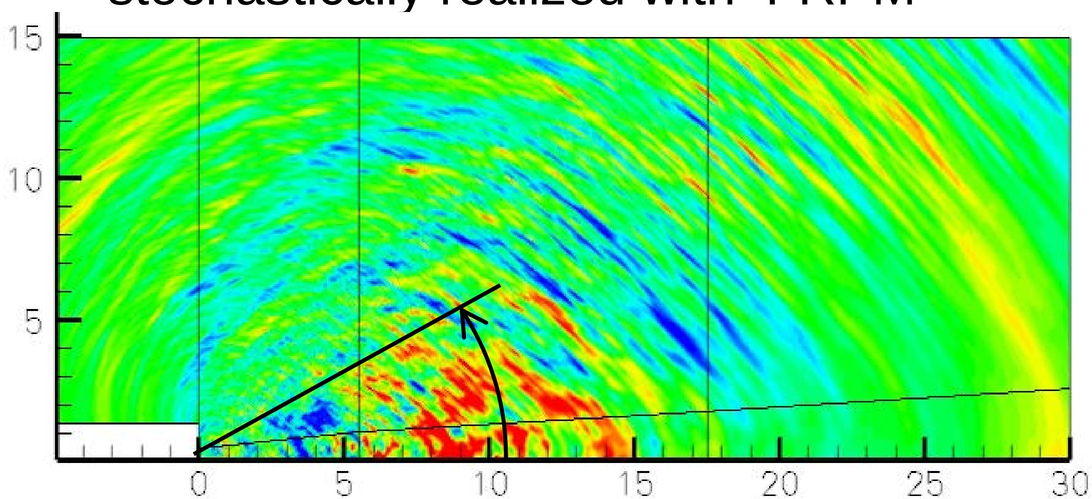


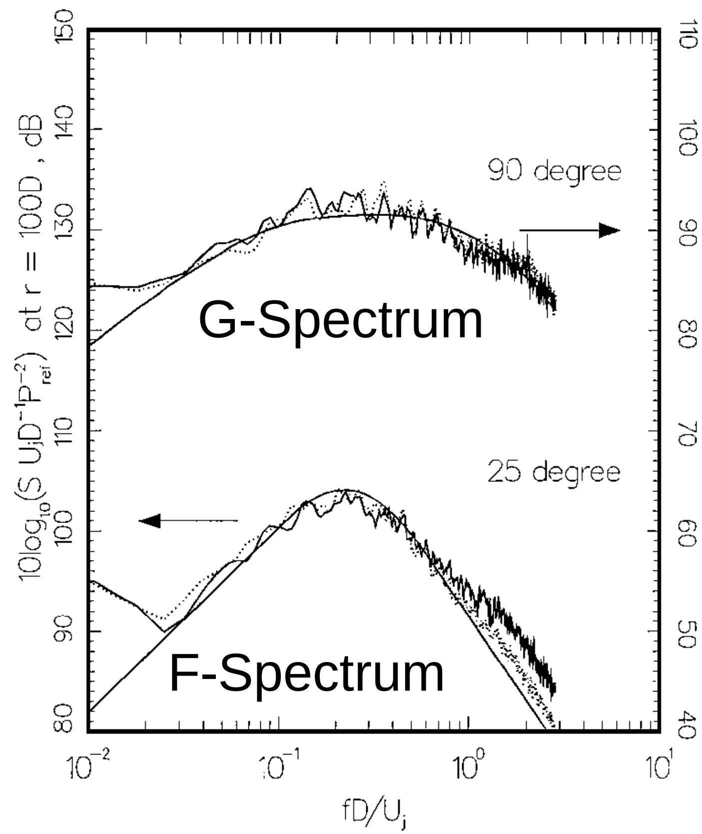
TKE

Time-scale

Length-scale

Source term of Tam/Auriault stochastically realized with FRPM





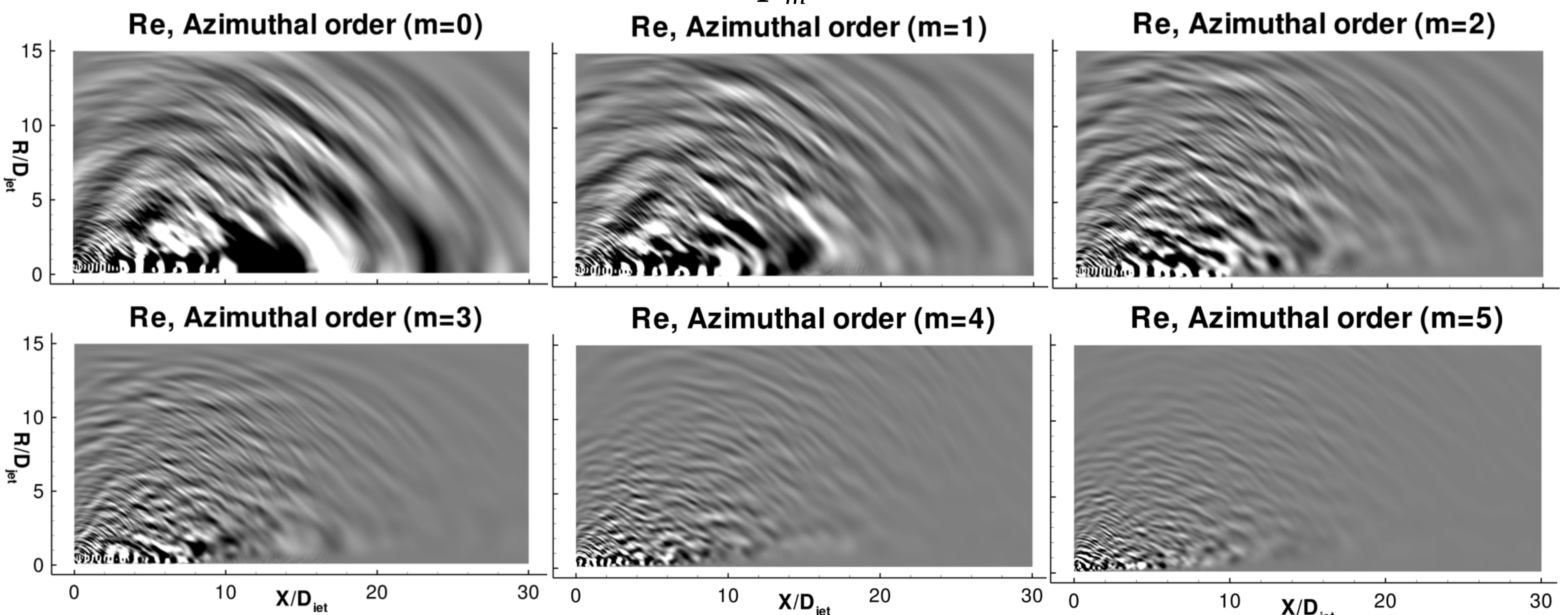
Source: C.K.W. Tam, K.B.M.Q.Zaman AIAA Journal Vol. 38, No. 4, April 2000

Azimuthal mode decomposition of problem

$$f(x,r,\phi,t) = \sum_{m=-\infty}^{\infty} \hat{f}_m(x,r,t)\exp(\mathrm{i}m\phi)$$

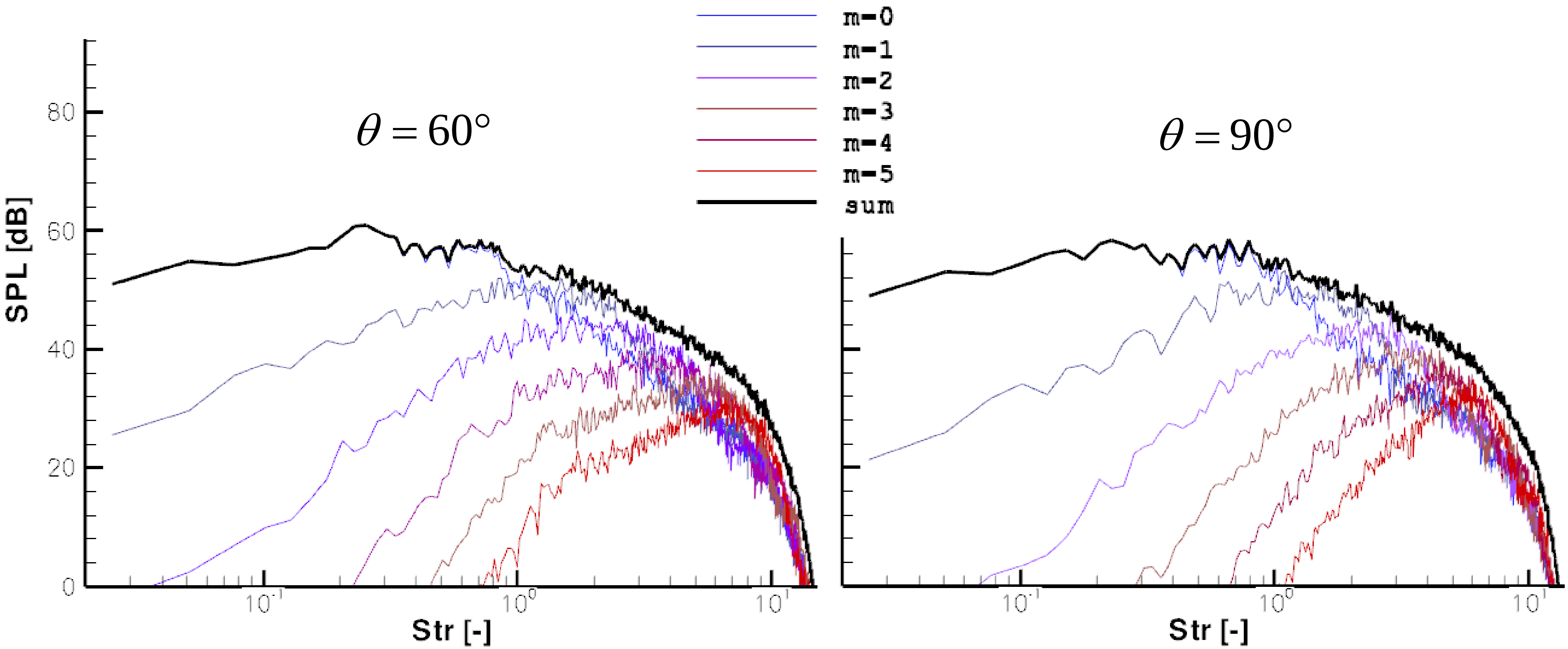
$\Rightarrow$ independent stochastic realization for each mode: $2m$ 2D problems

$\hat{p}_m$



Cold Single Stream Jet, Ma=0.75, D=0.5m, azimuthal mode between m=0 and m=5

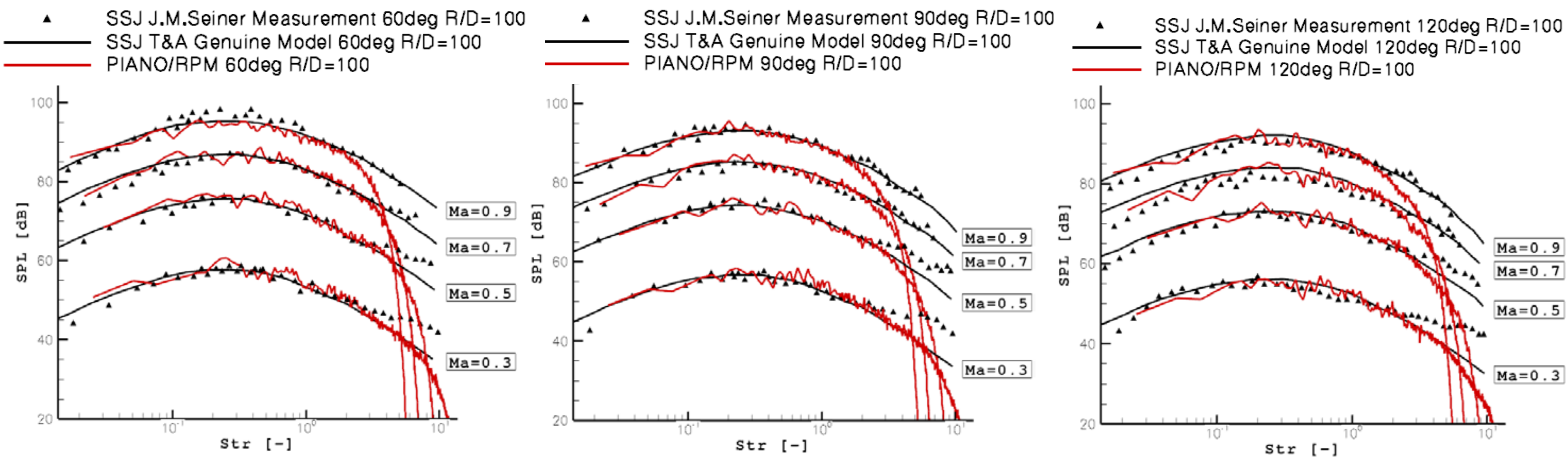
Azimuthal Components and Sum Spectra



"convergence" of overall spectrum at superposition of first 6 independently computed azimuthal modes (radial distance from the jet axis R/D=10)

Validation

Simple extrapolation of midfield (10D) CAA results to 100 D for comparison



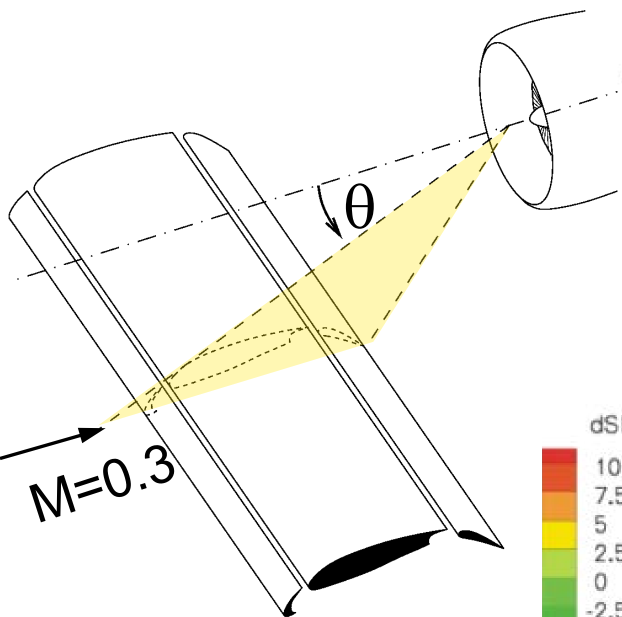
$\theta = 60°$ $\theta = 90°$ $\theta = 120°$

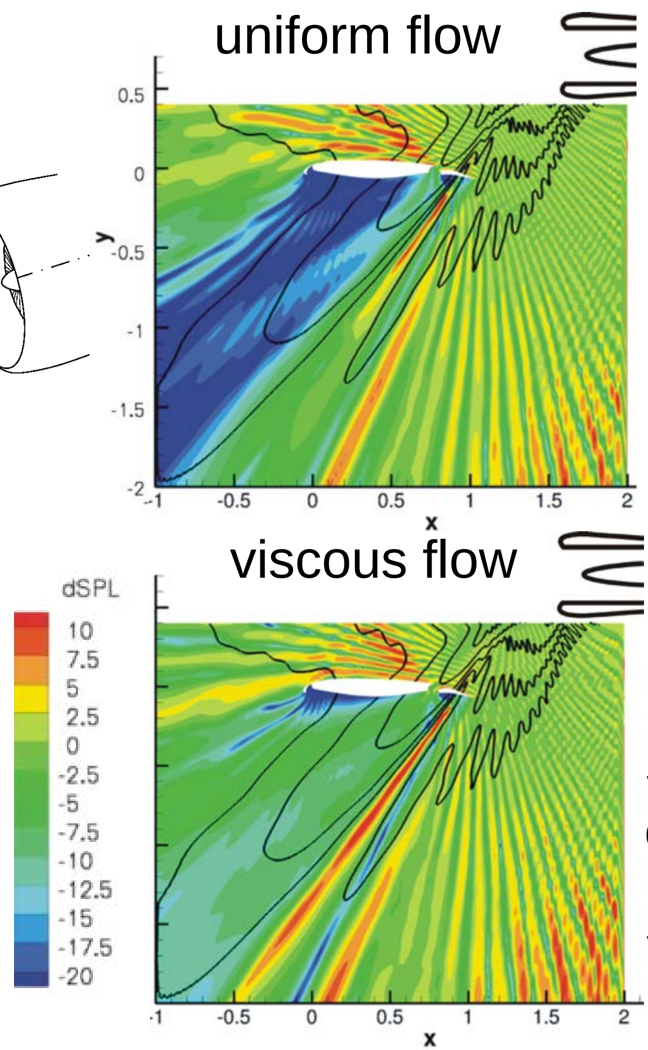
- experimental evidence that first 5 modes sufficient for sound field of serrated nozzle with 22 elements(!)
- perspective:
  low noise design for internal mixer & chevron nozzle

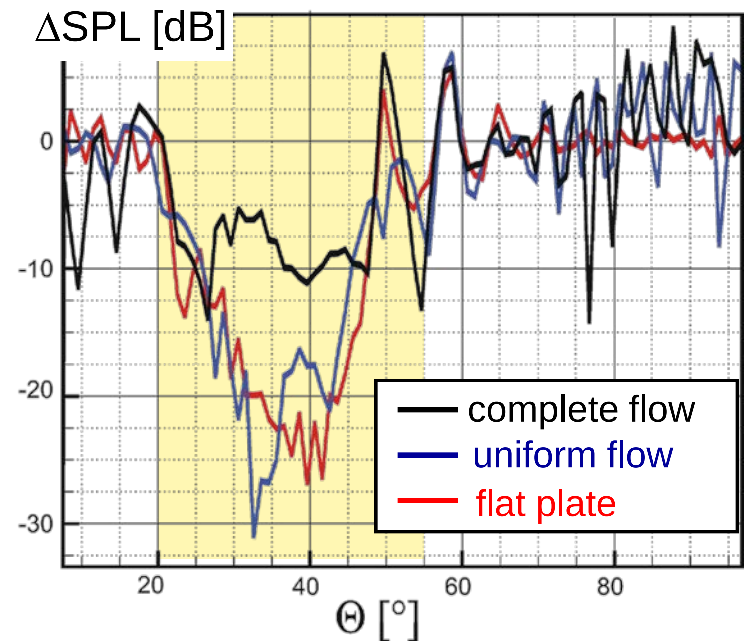
Propagation effects:

- Refraction at shear layers
- scattering by turbulence

Installation effect on fan tones at High Lift Wing



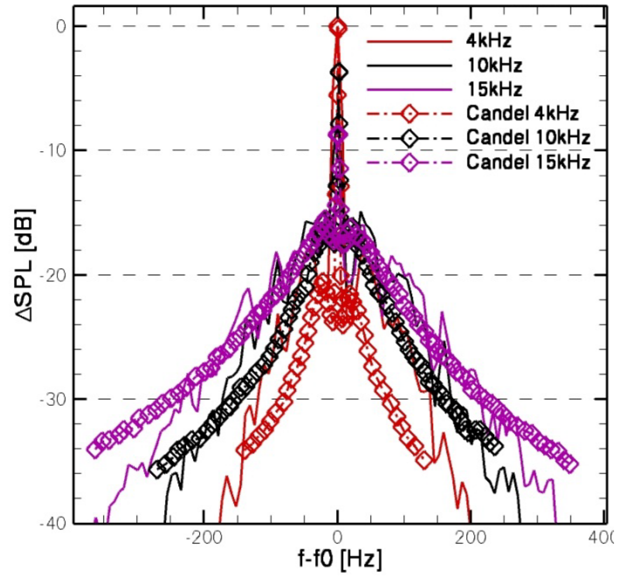


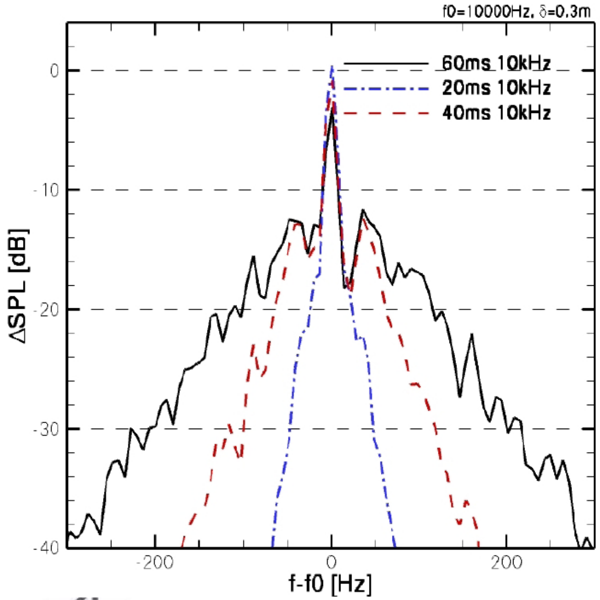


Simplified flow assumption overpredicts shielding by 10dB!

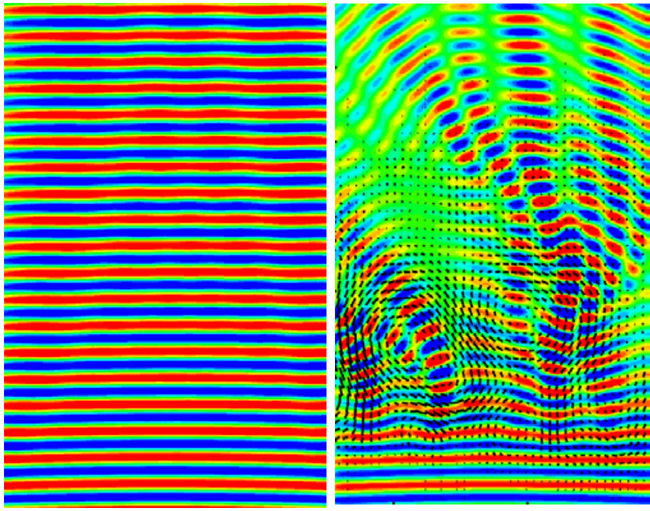
Strong viscous flow effects on noise shielding even at low M

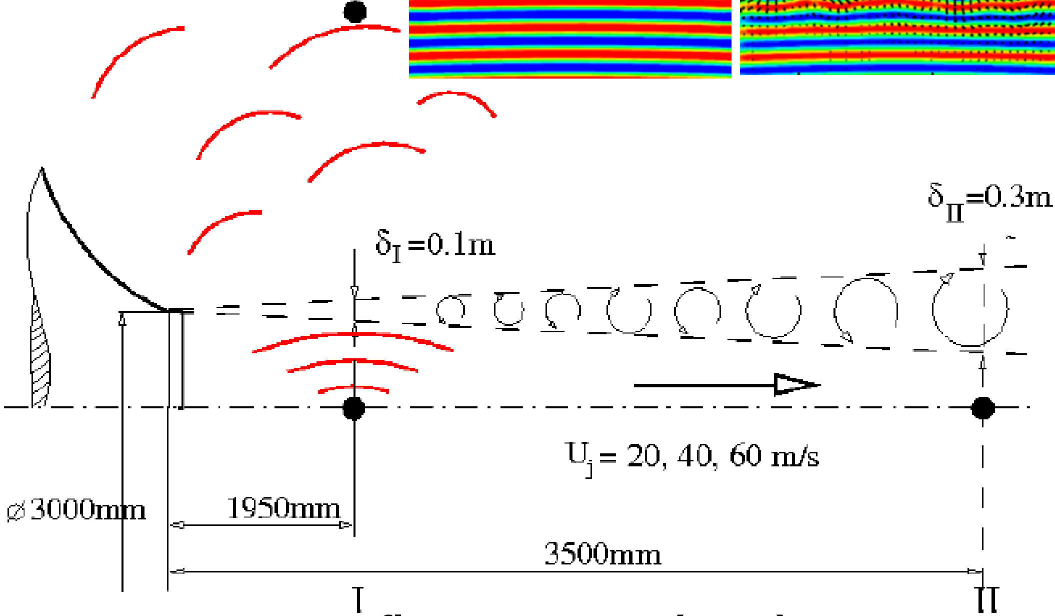
Tone scattering at turbulence (spectral broadening)





Wind tunnel shearlayer

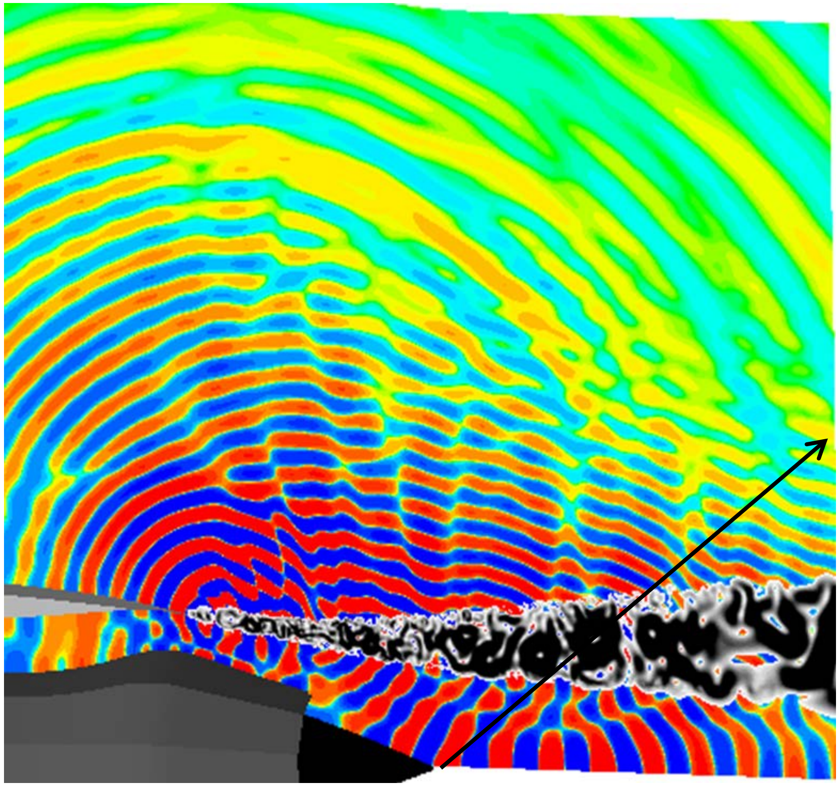


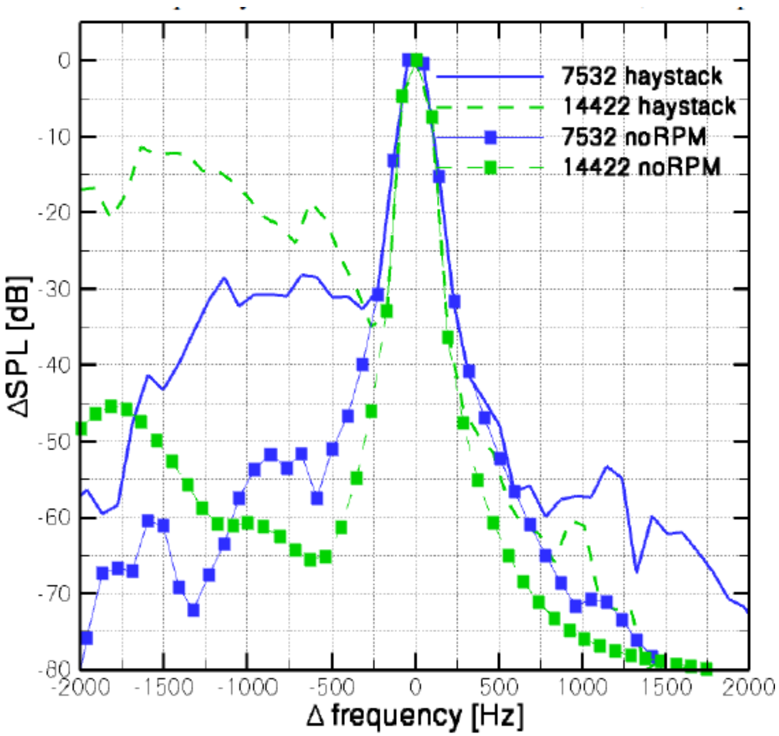


flow: FLUENT (RRD)
noise: PIANO

Tone scattering at turbulence (spectral broadening)

Jet shearlayer



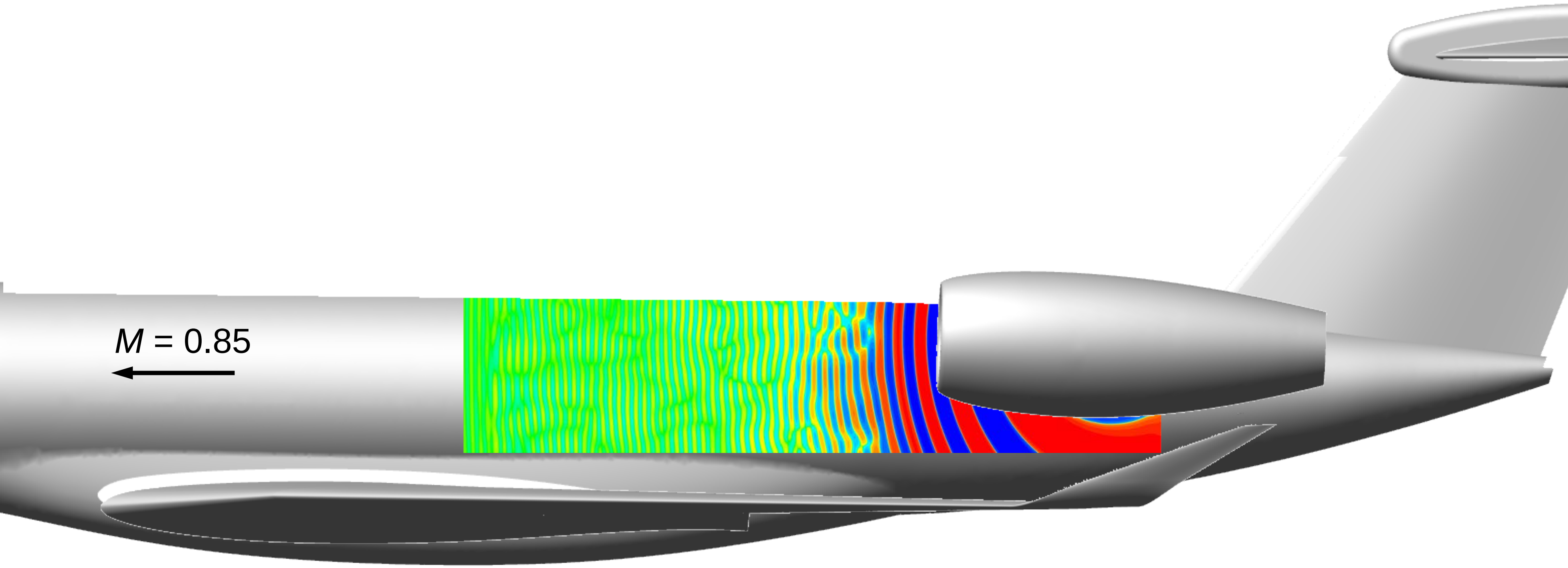


Prediction of surface pressures

Simulation of pressure fluctuations on fuselage

3 causes for turbulence related pressure fluctuations:

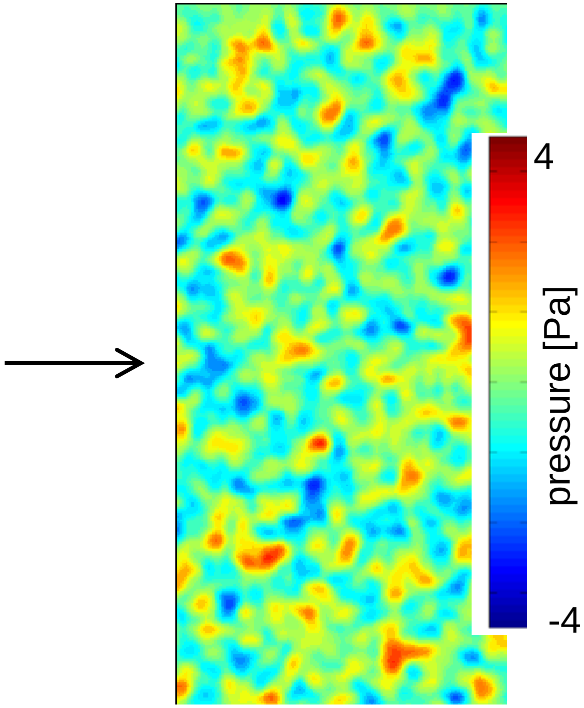
- hydrodynamic pressure field of turbulent boundary layer eddies
- jet noise
- scattering of engine tones in turbulent boundary layer

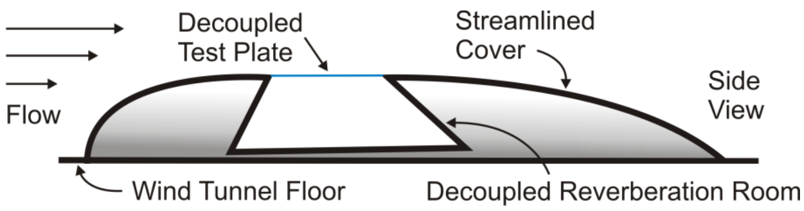


Fuselage surface pressure fluctuations from TBL

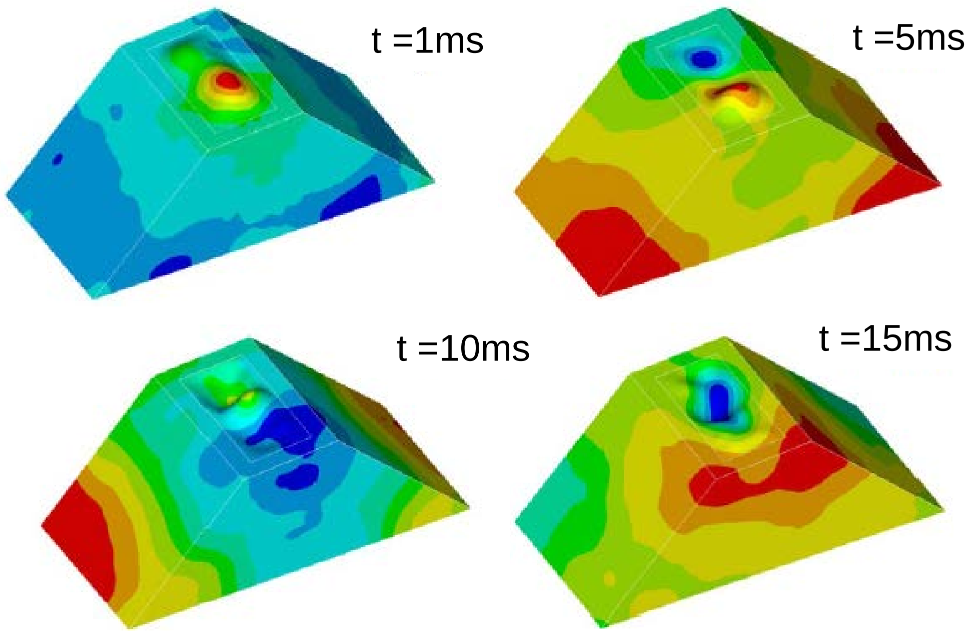
Stochastic wall pressure model

RPM stochastic excitation
(instantaneous pressue,
von above onto plate)



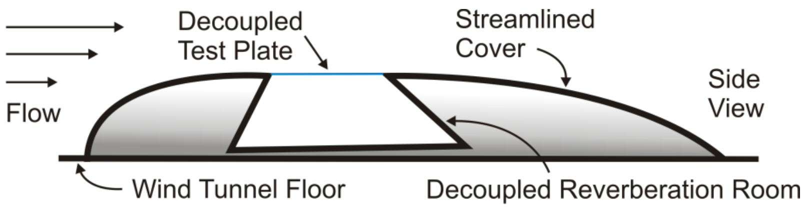


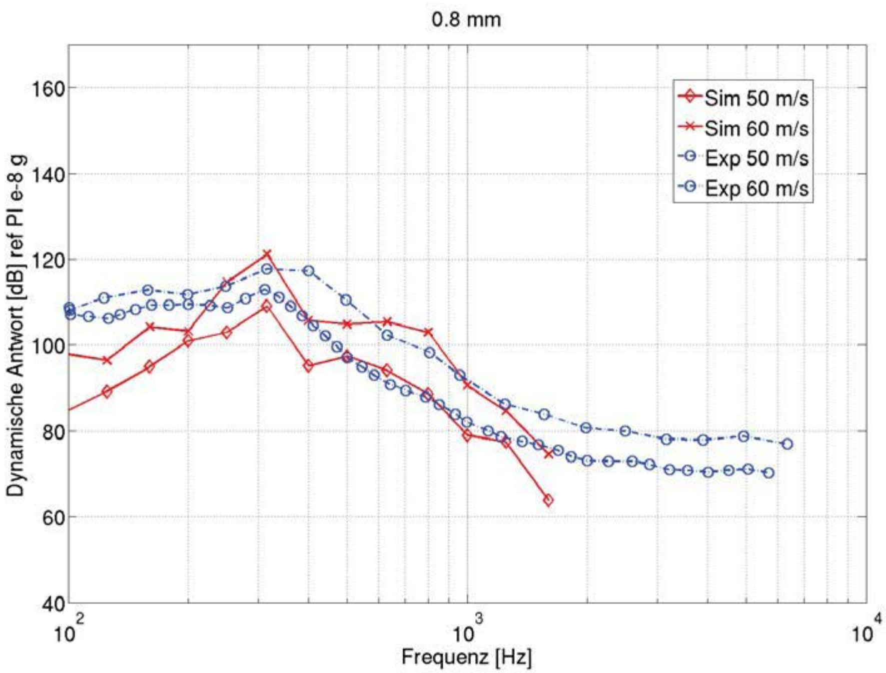
Coupling with ANSYS (time domain)



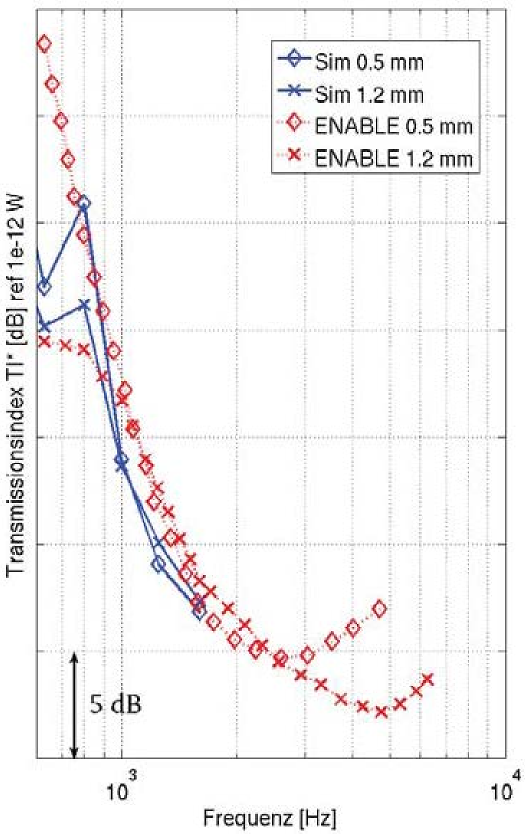
Vibration of 1.2mm Aluminium plate
(ENABLE EU-Project).

Validation of coupling CAA - CSM



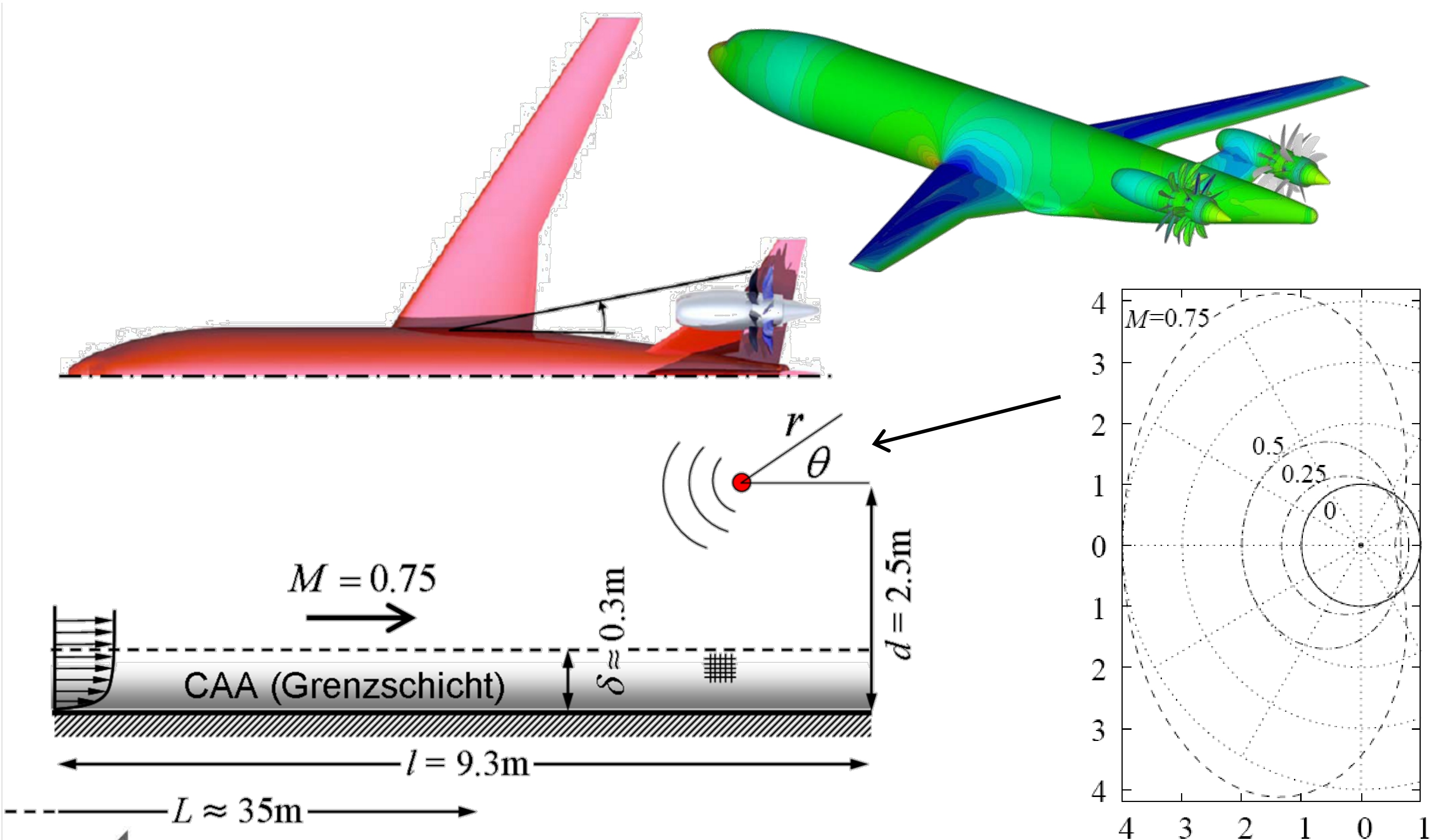


Dynamic response of plate



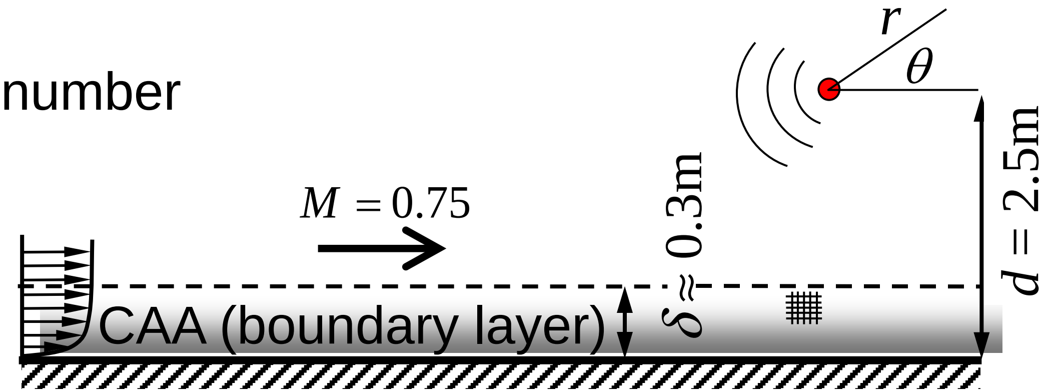
Transmission Index

Fuselage sound pressure level from engine tone signals

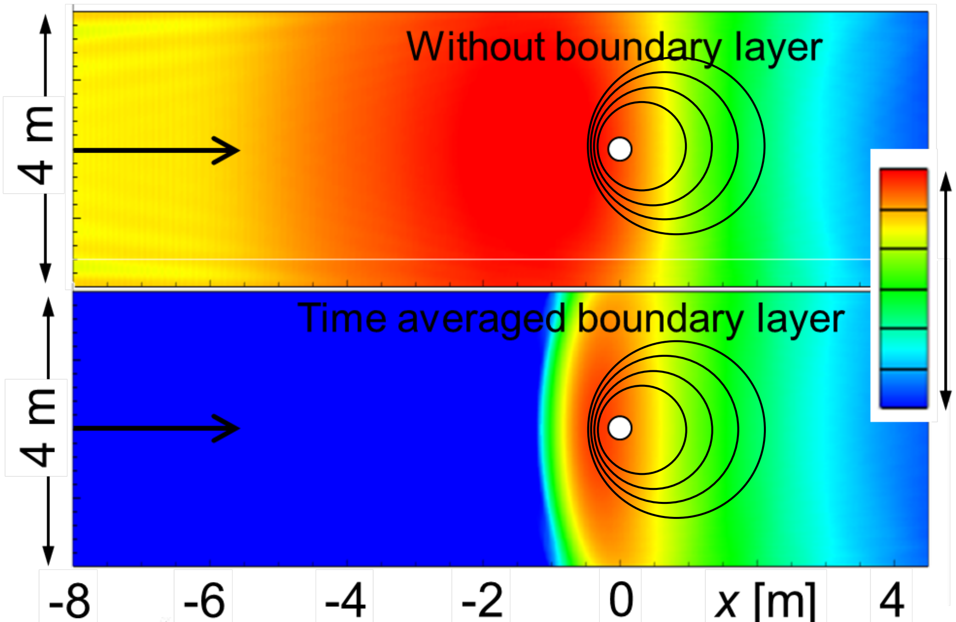


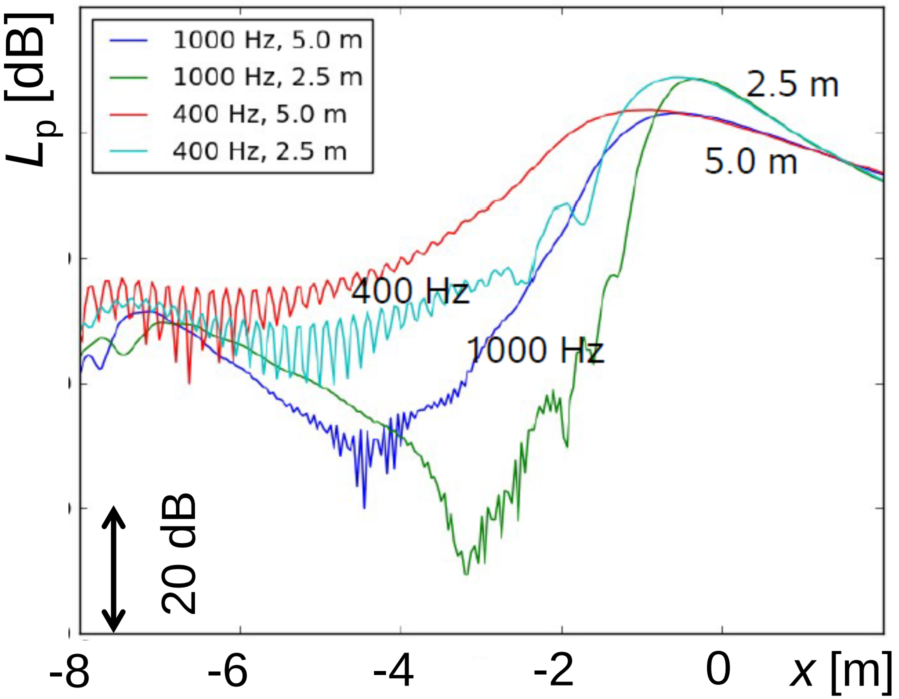
Fuselage sound pressure level from engine tone signals

- realistic Reynolds number
- RANS/FRPM/LEE



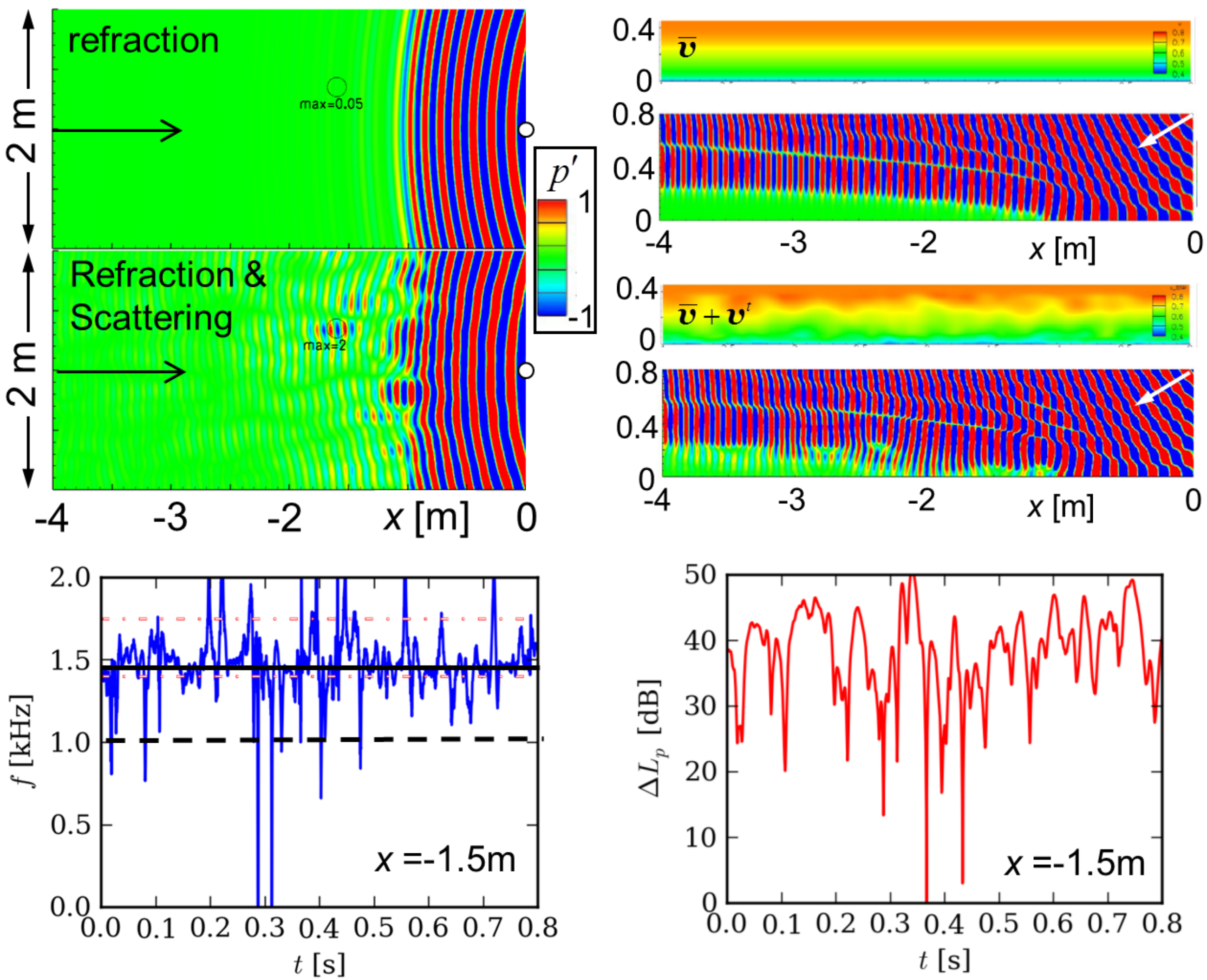
Surface pressure levels point source





Siefert, Delfs, Caruelle, AIAA2011

Fuselage sound pressure level from engine tone signals



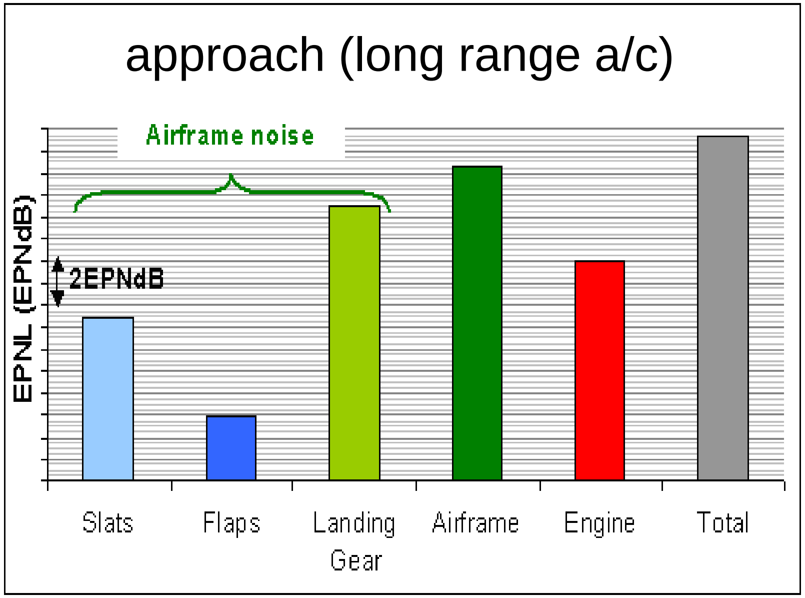
Refraction & Scattering at turb. eddies $\Rightarrow$ Doppler shift (position dependent) !

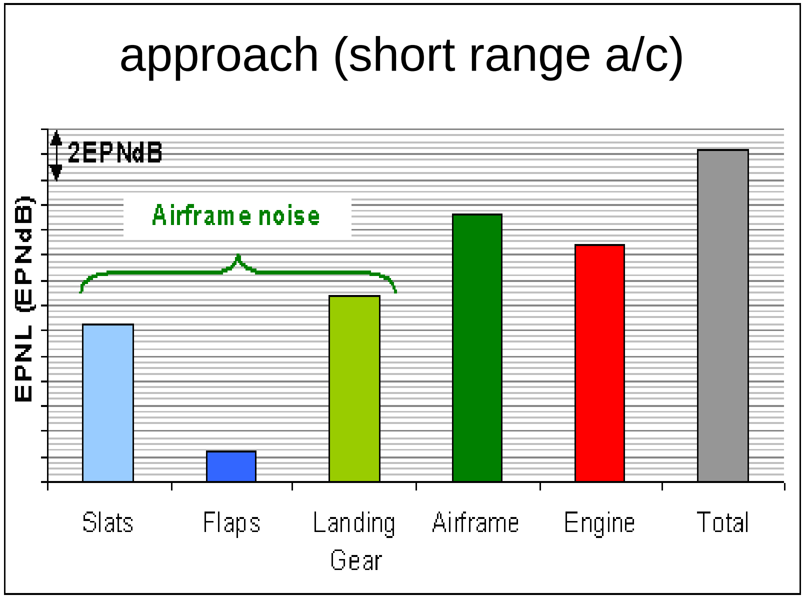
Siefert, Delfs, Caruelle, AIAA2011-2847

Reduction of aerodynamic noise

- by means of aero- / acoustic design
- by means of source manipulation with add-on technologies

Importance of sources at a/c level

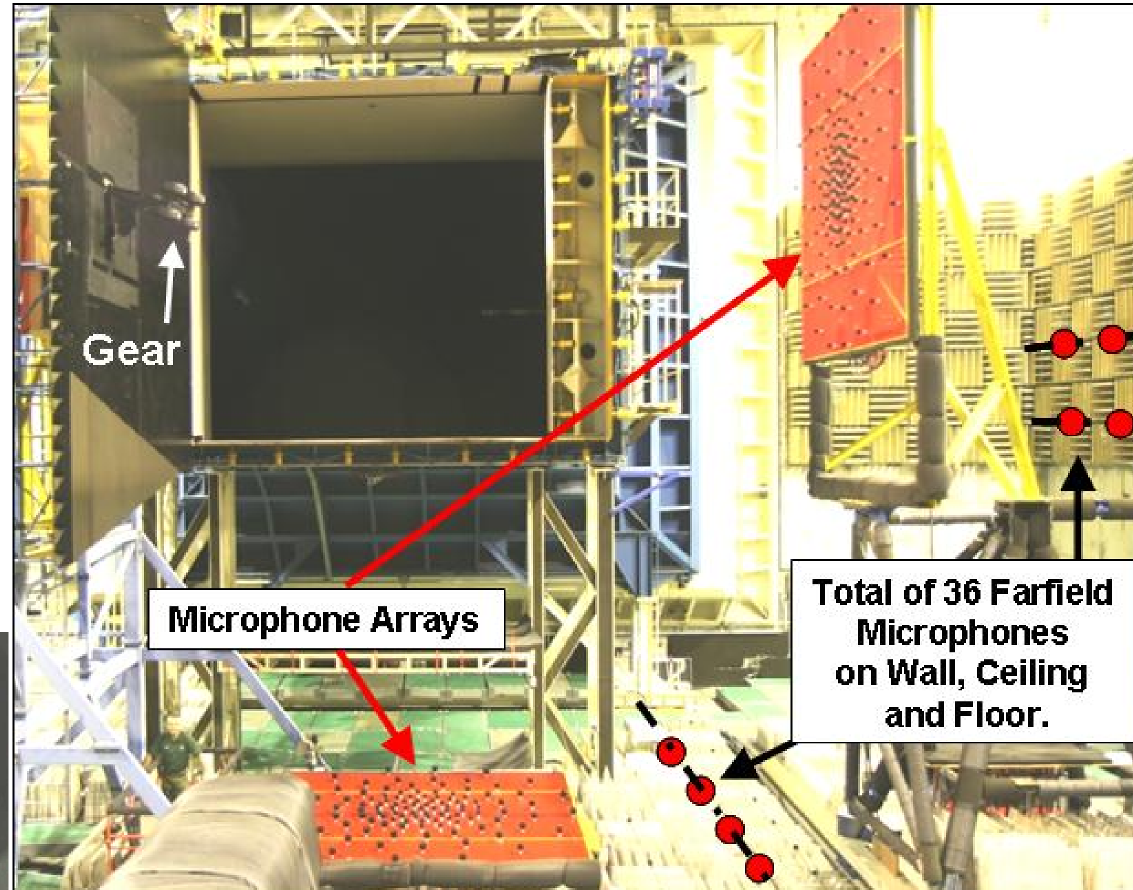




source: Airbus

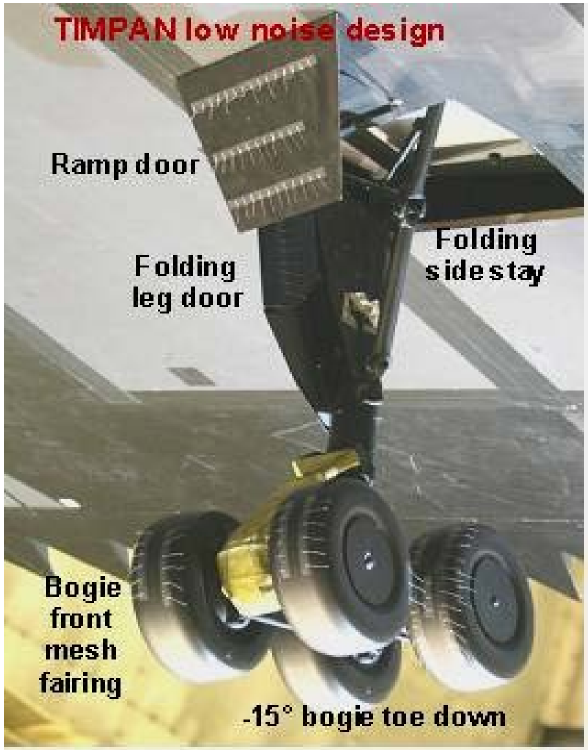
Investigation of landing gear noise

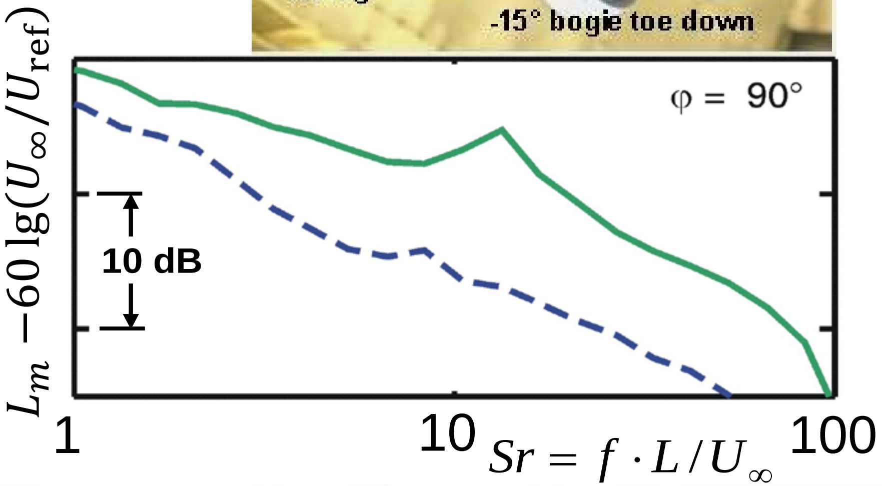
- ¼-scale A340-type main LG at side plate in DNW-LLF 6m x 6m open test section
- Far field microphones for 3D directivity, 0.1 kHz < f < 20 kHz
- Two microphone arrays (from below, from side)



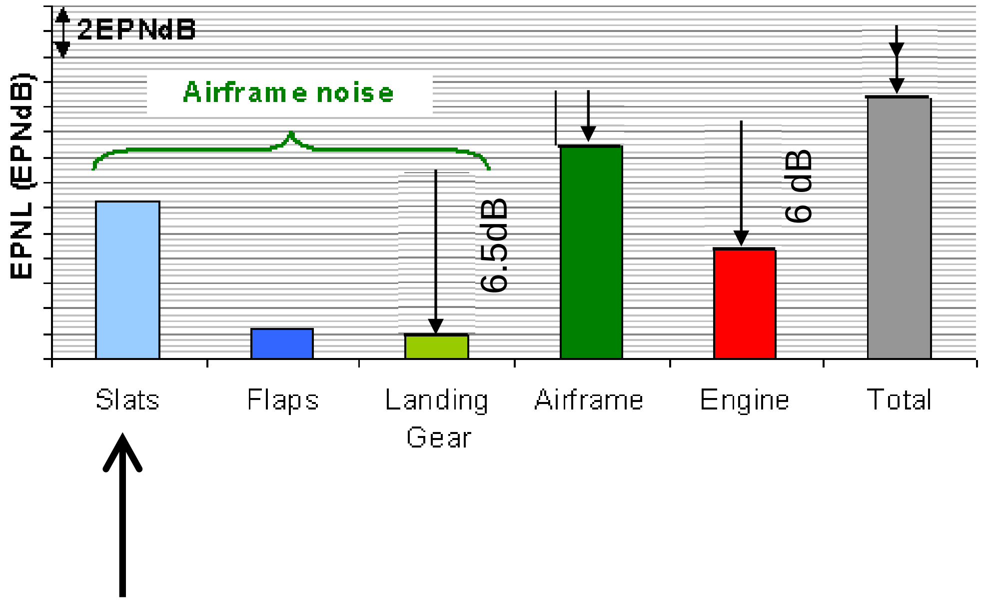
Noise reduction potential at Landing Gear

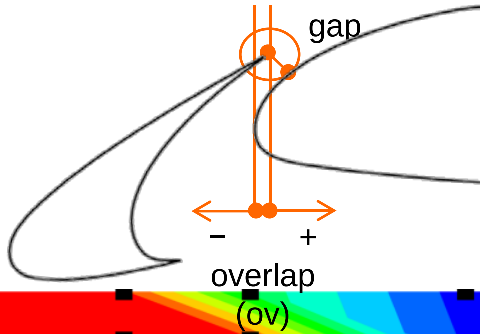
- Optimal combination of measures yields up to 8 dB(A) of noise reduction (broadband)
- Reduction most effective upstream and + for high frequencies
- Measures include:
  - -15° angle of attack (toe down)
  - Flow permeable fairings at bogie articulation links
  - (partial) brake farings
  - Tiltable LG-door with new side stay and ramp door





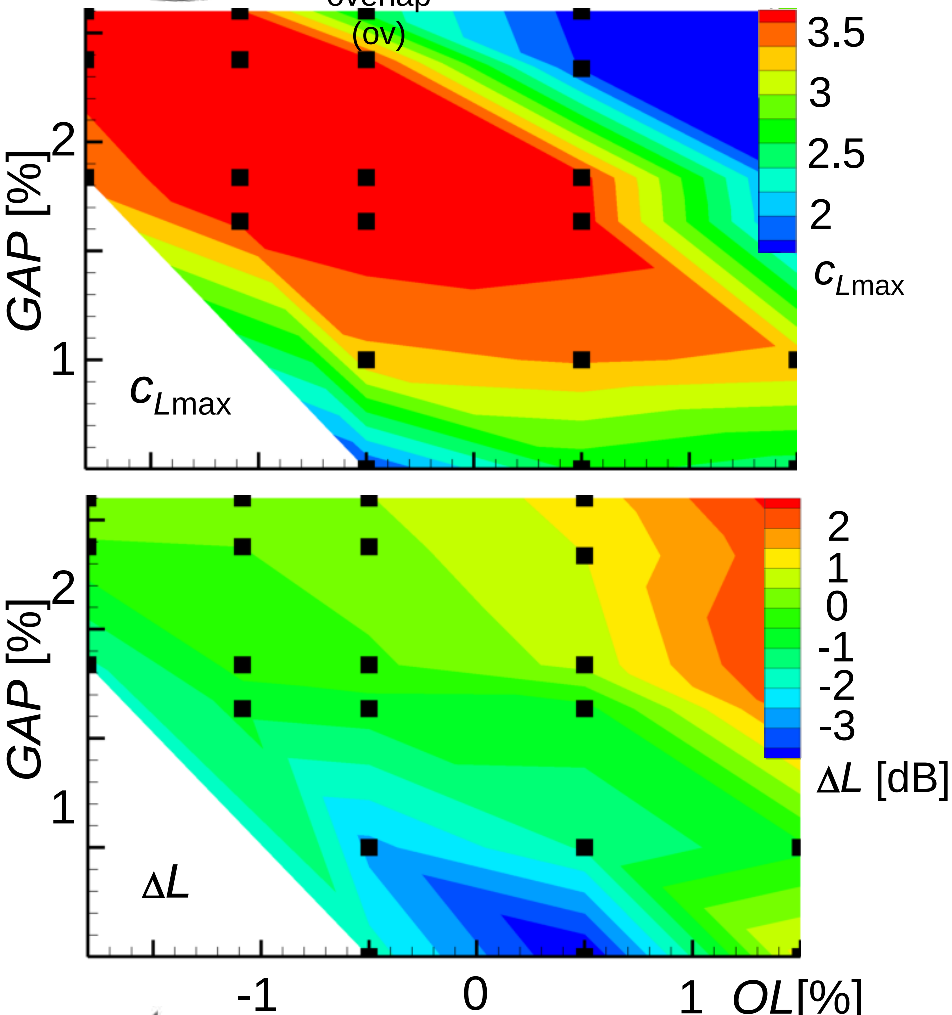
Importance of sources at a/c level

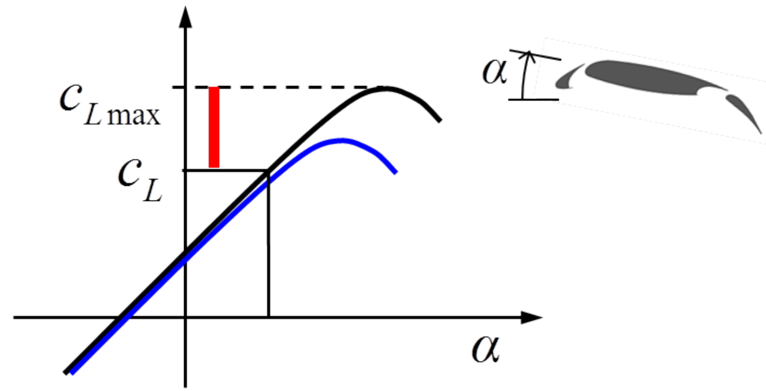




Simulation based aeroacoustic Design

Optimum slat settings





lifting force $\quad F_L = c_L \frac{\rho}{2} v^2 A \quad = c_{L\max} \frac{\rho}{2} v_s^2 A$

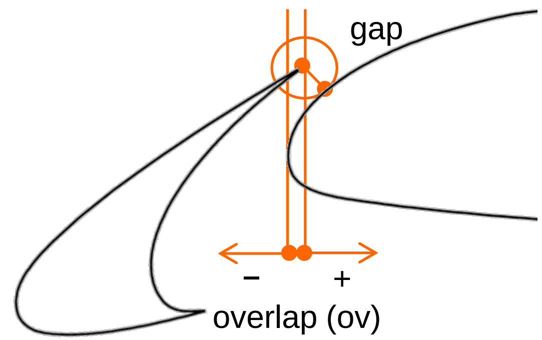
Minimum speed $\quad v \geq C\, v_s \quad \Rightarrow c_L \leq c_{L\max} / C^2$

$$\Rightarrow c_{L\max} v^2 = const$$

$$\frac{v}{v_{ref}} = \sqrt{\frac{c_{L\max_{ref}}}{c_{L\max}}} \quad \Rightarrow p_{rms}^2 \sim v^5 \sim c_{L\max}^{-5/2}$$

flow: TAU
sound: PIANO

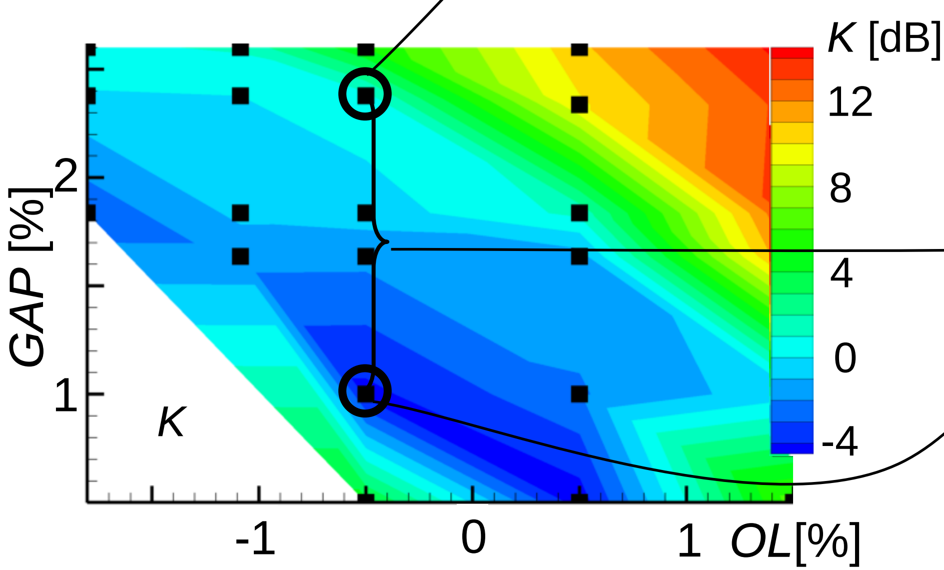
Simulation based aeroacoustic Design

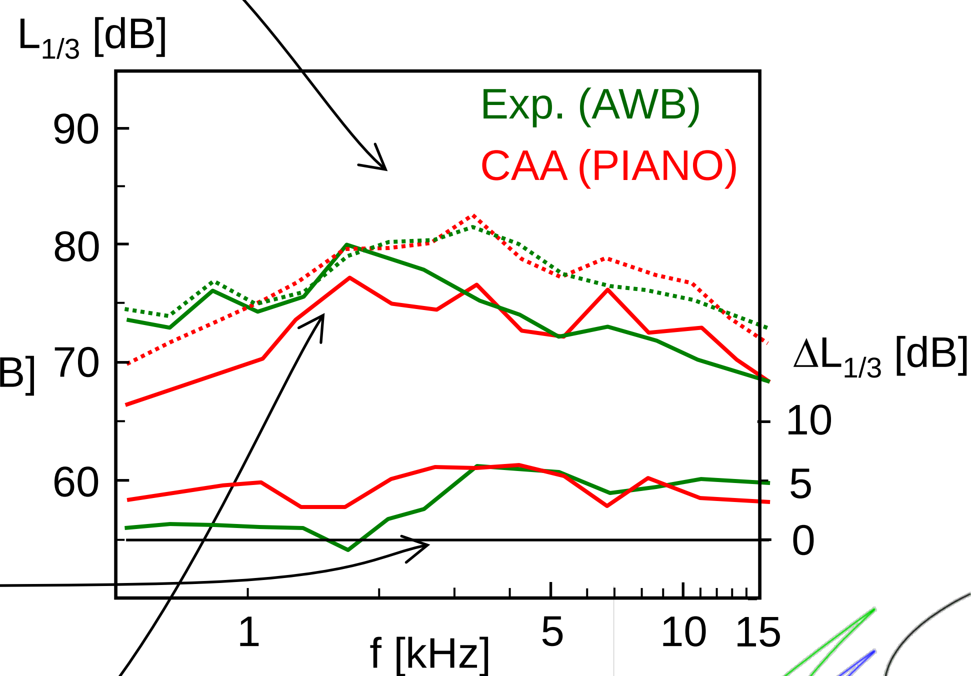


Optimum slat settings

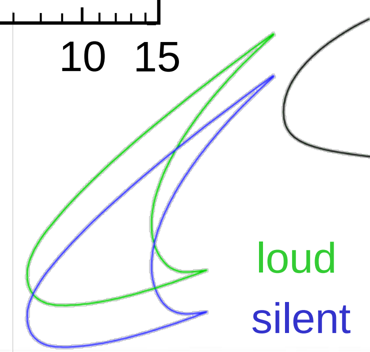
⇒ Aeroacoustic cost function

$K = \Delta SPL + 10\lg(CLmax_{ref}/CLmax)^{5/2}$



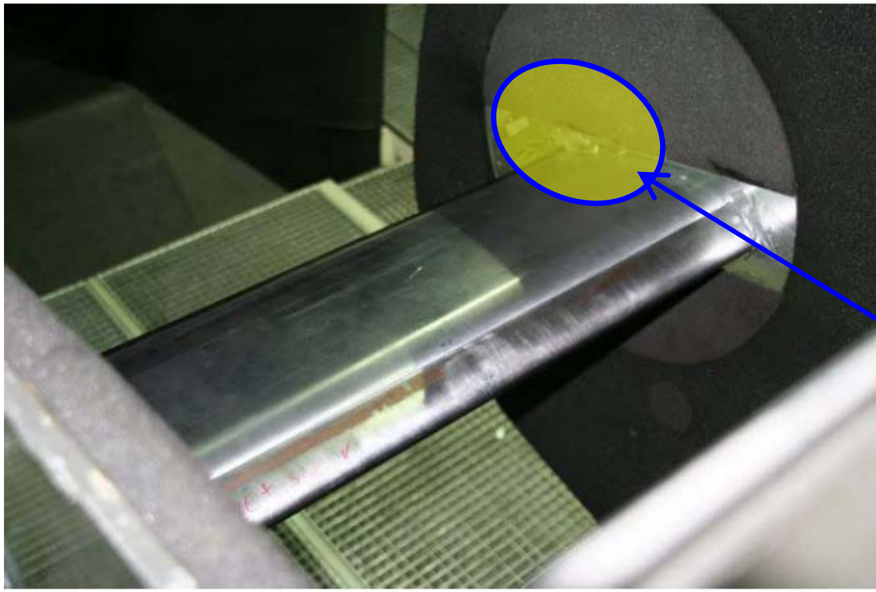


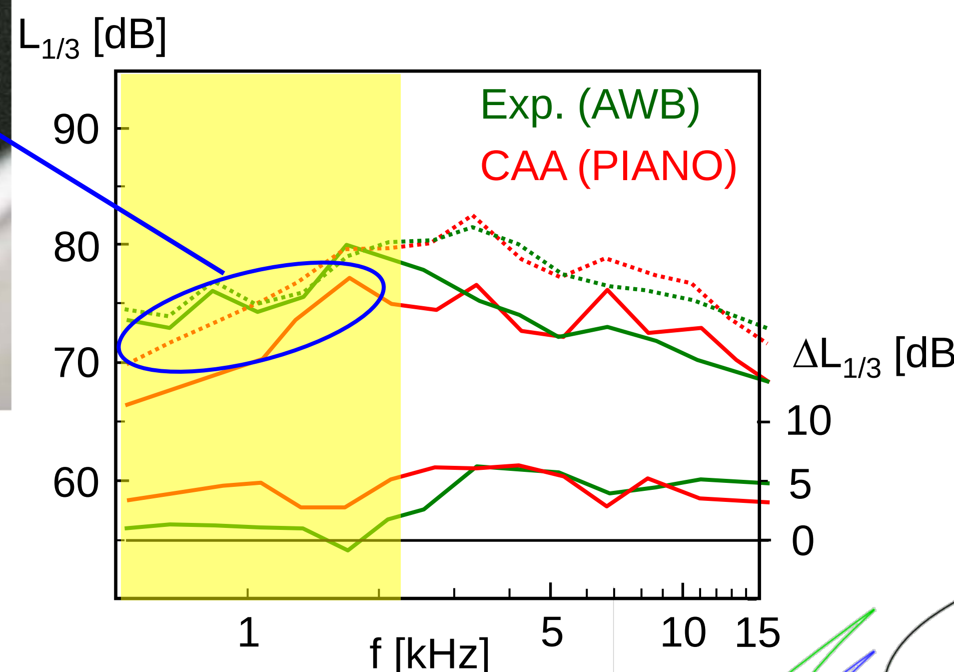
flow: TAU
sound: PIANO

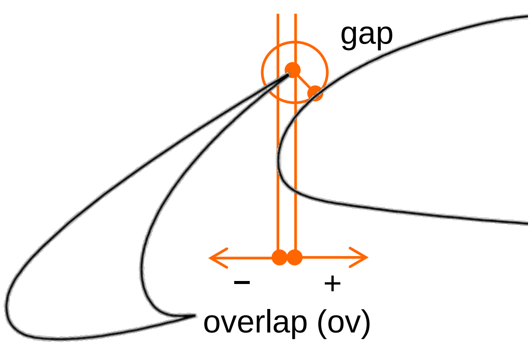


Simulation based aeroacoustic Design

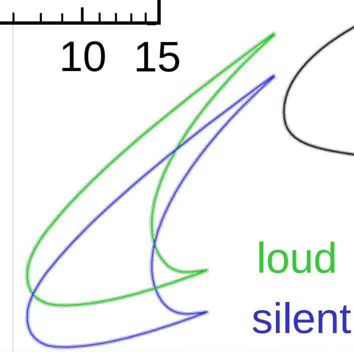
Optimum slat settings



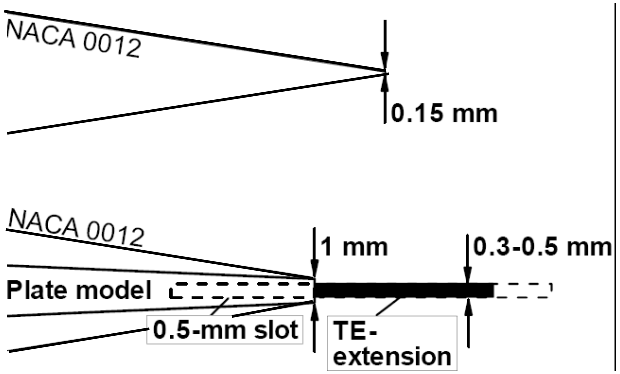


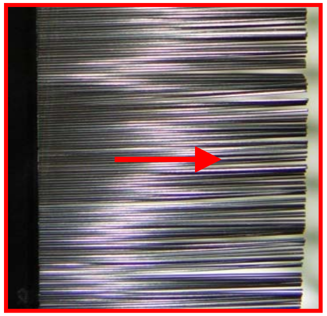


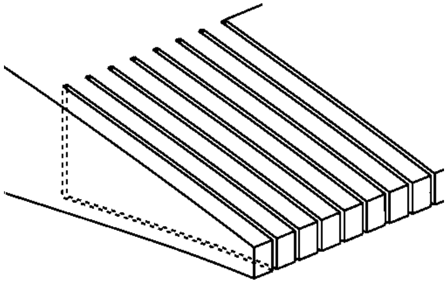
flow: TAU
sound: PIANO

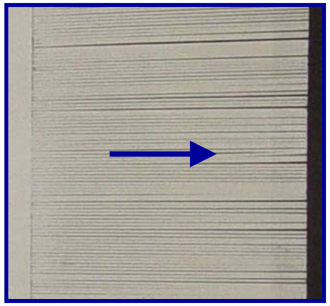


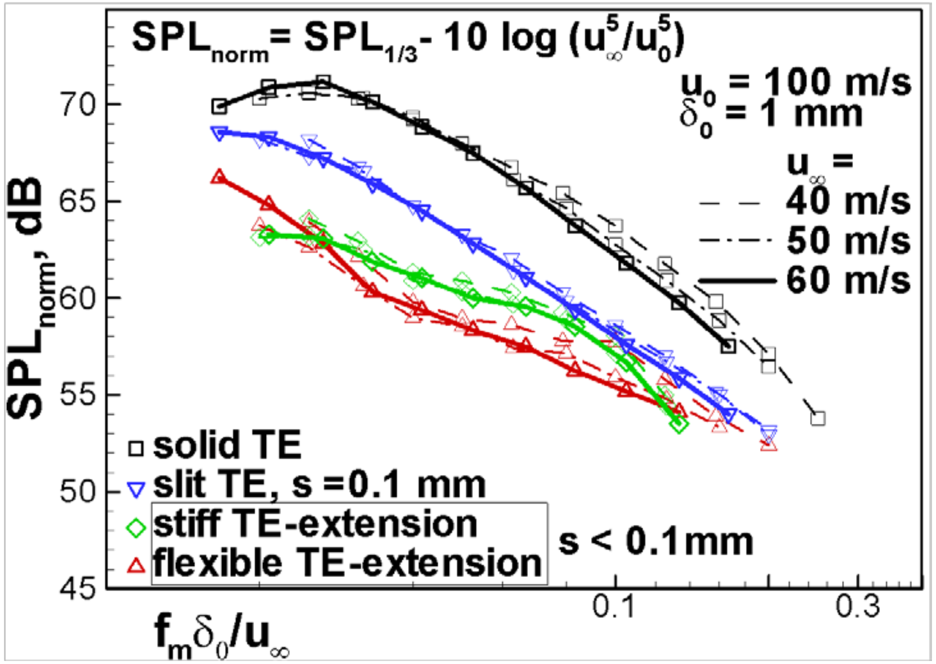
Noise reduction technologies – Trailing edge modifications









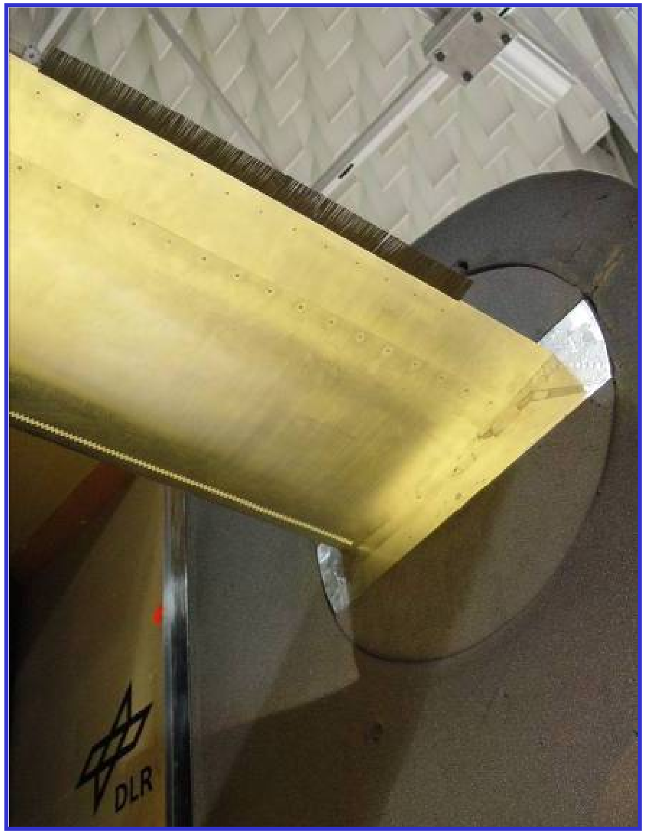


Micro Slits

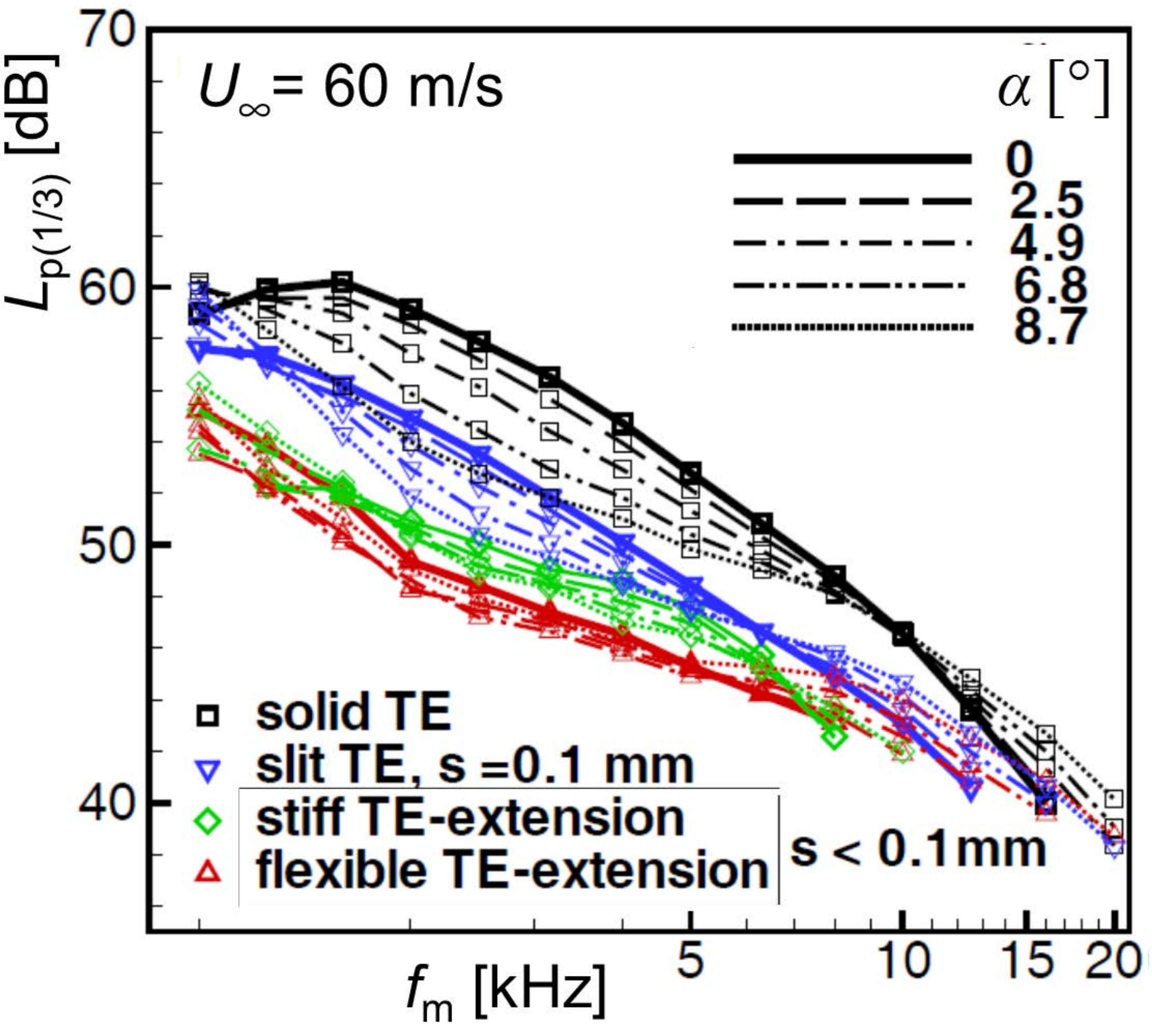
RANS: practically no lift degradation*

*) Ortmann, J., Wild, J., *Journal of Aircraft*, Vol. 44, No.4, 2007

Trailing Edge noise reduction under aerodynamic load



NACA0012

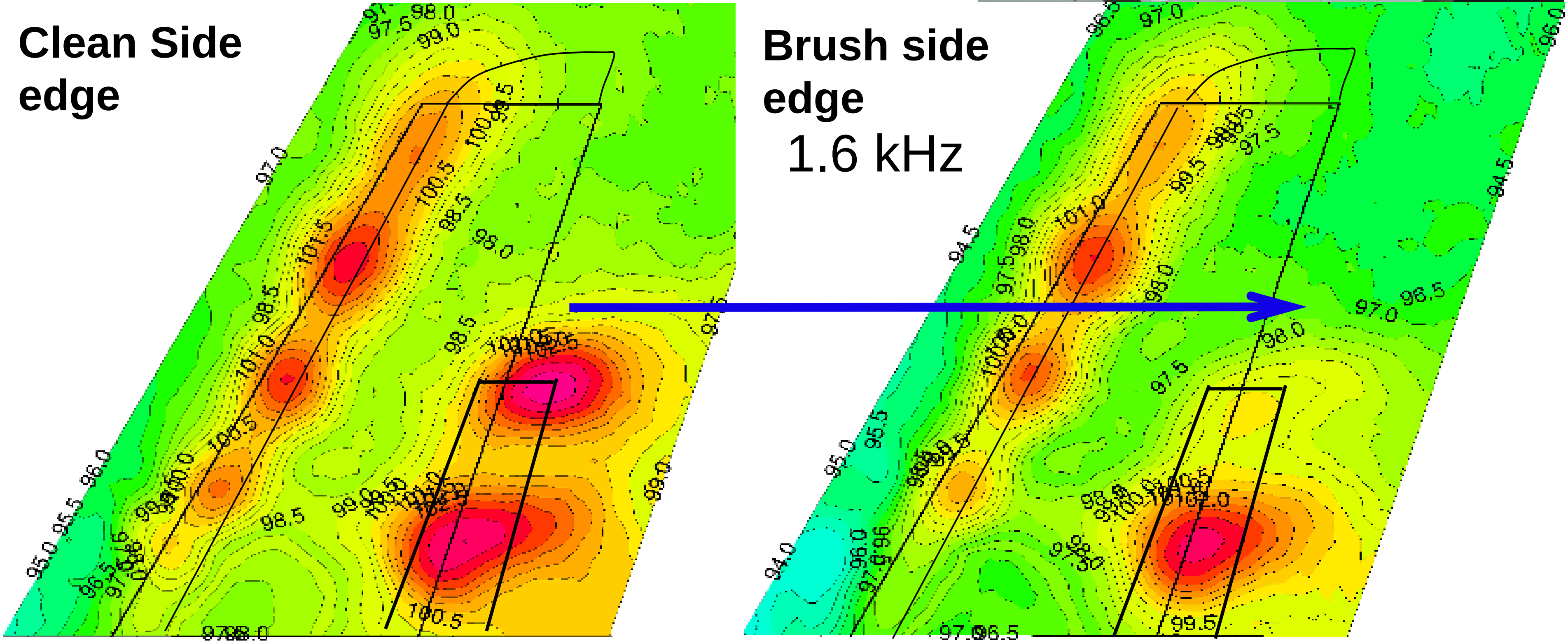


Broadband noise reduction at edges

Clean Side edge

Brush side edge

1.6 kHz



Summary

- Realistic prediction of propeller noise requires consideration of aerodynamic+ acoustic istallation
- Effects of scattering of fuselage turbulent boundary layer may be excessively large in cruise flight (little knowledge, no validation concept)
- RANS+FRPM+LEE/APE concept useable in a broad range of applications, requiring comparatively small computational effort
- Design of low noise components feasible on basis of ΔSPLs
- Flow permeable materials show high reduction potential, mechanism barely understood, not (yet) possible to predict numerical

Perspective

- Need to simulate effect of flow permeable materials for reduction of airframe noise for targeted low noise design and efficient use (SFB880)
- Validation of CAA is very important topic for the future:
  - Large scale WT tests to avoid artefacts (e.g. tone phenomena)
  - Still more silent wind tunnels with high flow quality for noise source of low intensity
  - Better aeroacoustic wind tunnel corrections („how valid is a validation test?“)
- Generalization of stochastic turbulence models (anisotropy)
- Establishment of unstructured CAA solver for complex component geometries (landing gears, details of high lift systems, air systems etc.)
- Mid-Fidelity CAA for non-empiric noise prediction of complete wings/LGs
- Adaptive / active reduction of flow noise sources

App1

App2

App3

DLR

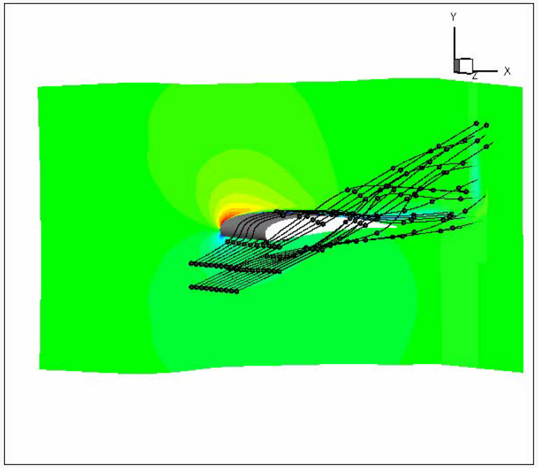
A/C Components: RANS/CAA Approach

RANS → **4D stochastic source description** → **Perturb. Equ. LEE/APE**

TAU **FRPM** **PIANO**

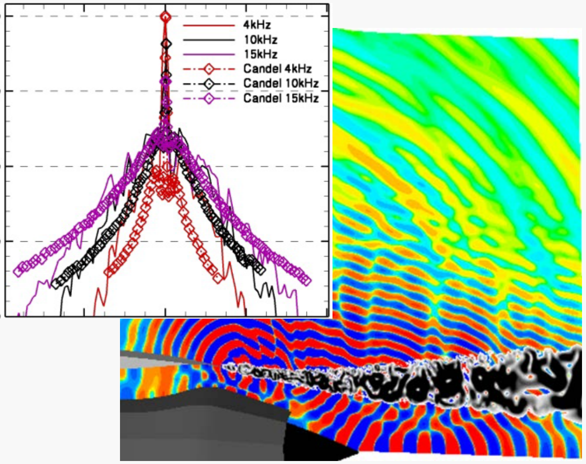
⇒ very much faster than scale resolving simulations

High Lift Noise



Flow: TAU/ noise: PIANO

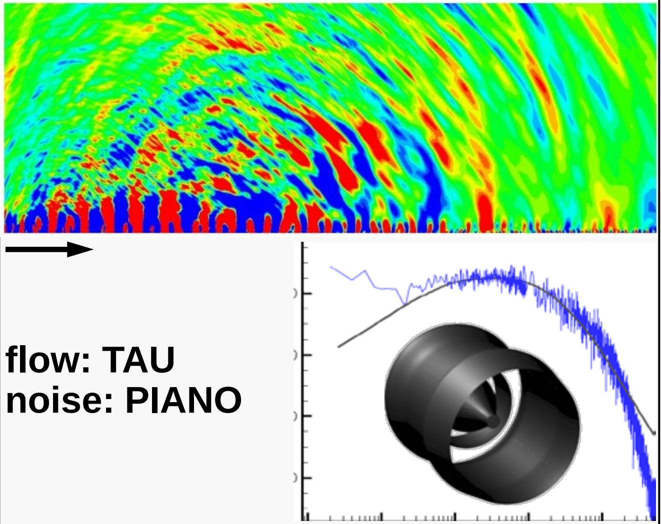
tone scattering at turbulence



flow: FLUENT (RRD)
noise: PIANO

EU „TURNEX“ (DLR/RRD)

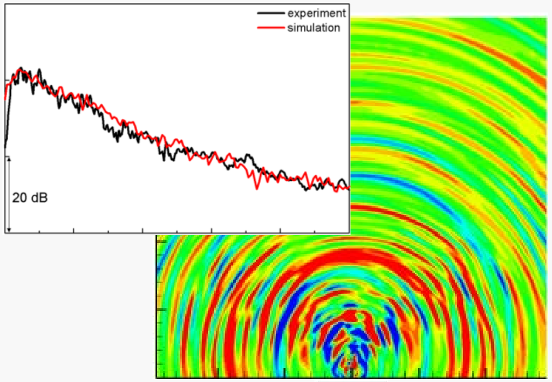
jet noise (incl. jet/flap)



flow: TAU
noise: PIANO

Lufo III „FREQUENZ“ (DLR/RRD)

combustion noise

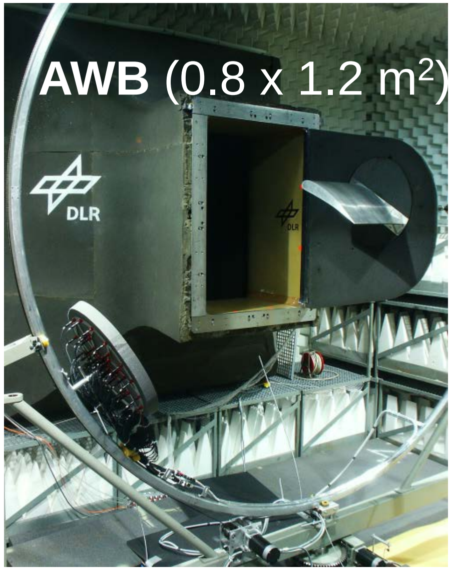


flow: THETA
noise: PIANO

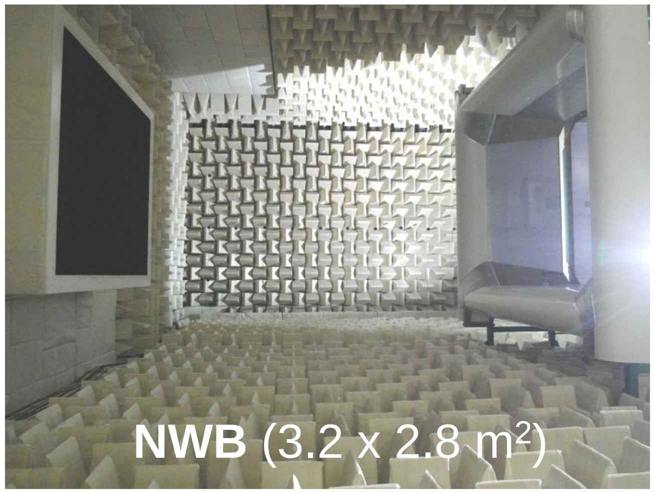
DLR A Flame

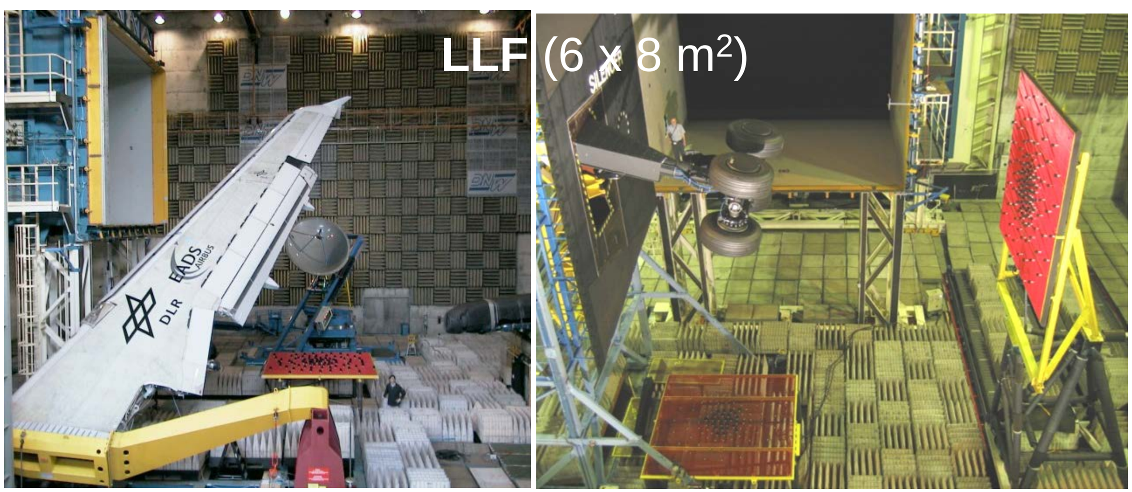
DLR „AVANTGARDE“ (AS/VT)

Experimental facilities

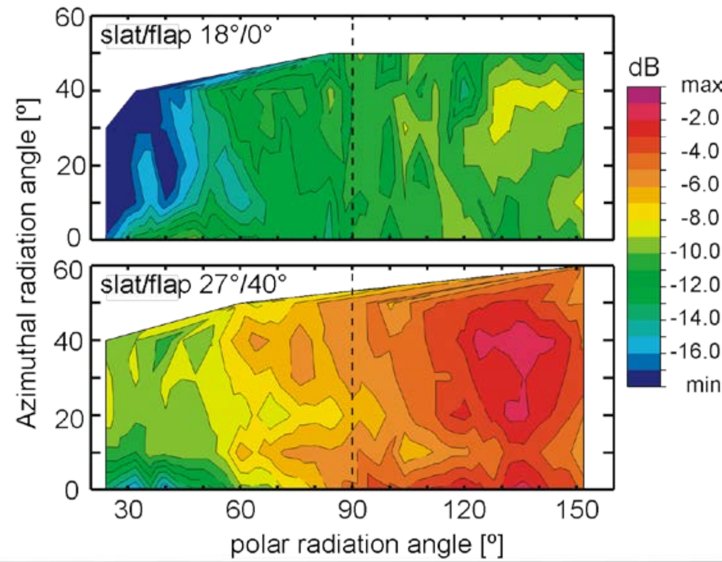


Aeroacoustic Wind tunnels

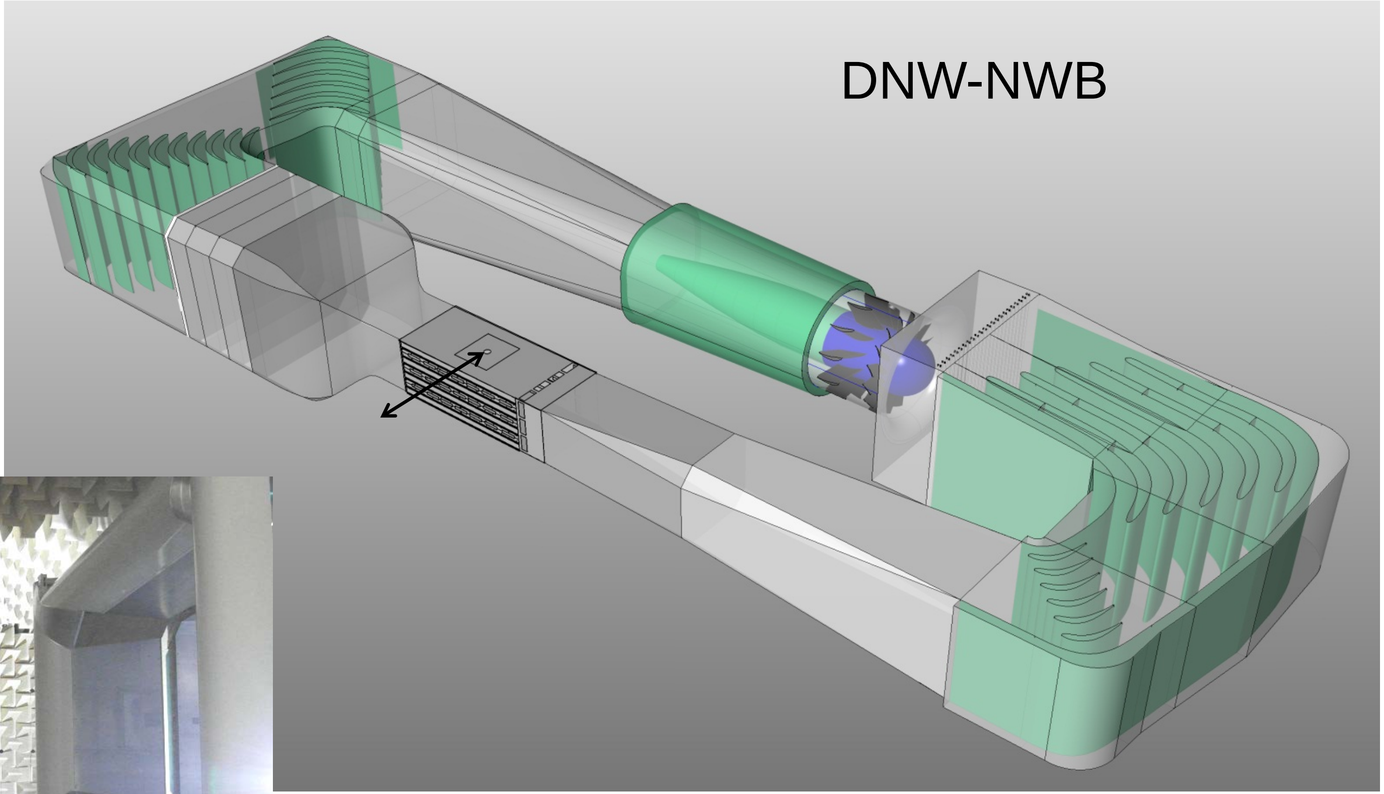


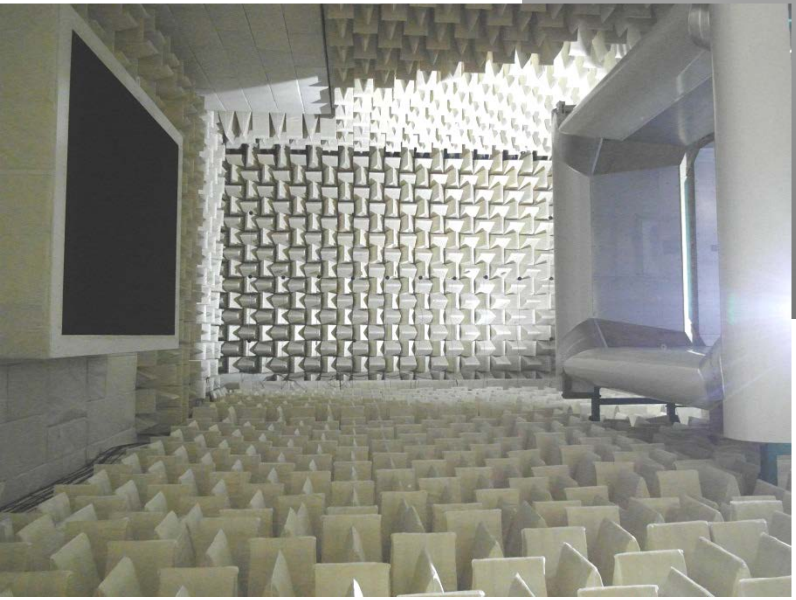


30 remote controlled wireless stations (2 microphones each)



Aeroacoustic Windtunnel DNW-NWB Braunschweig
(Inauguration 02. Dec.2010)

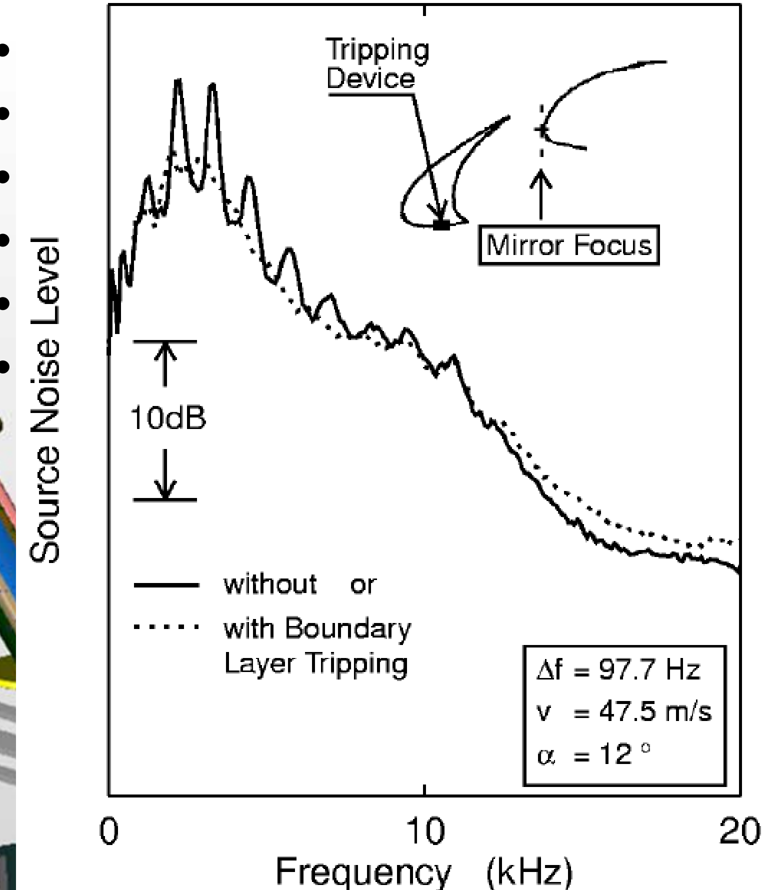


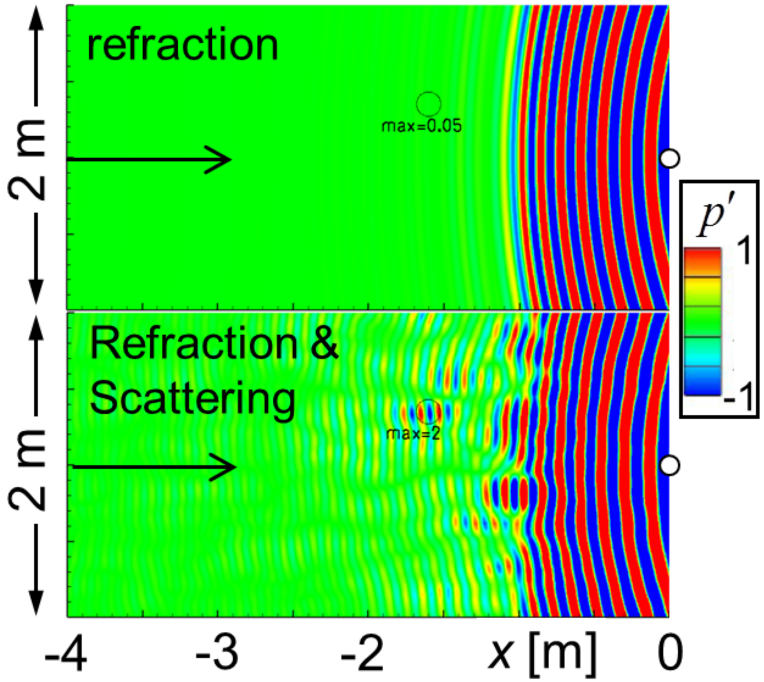


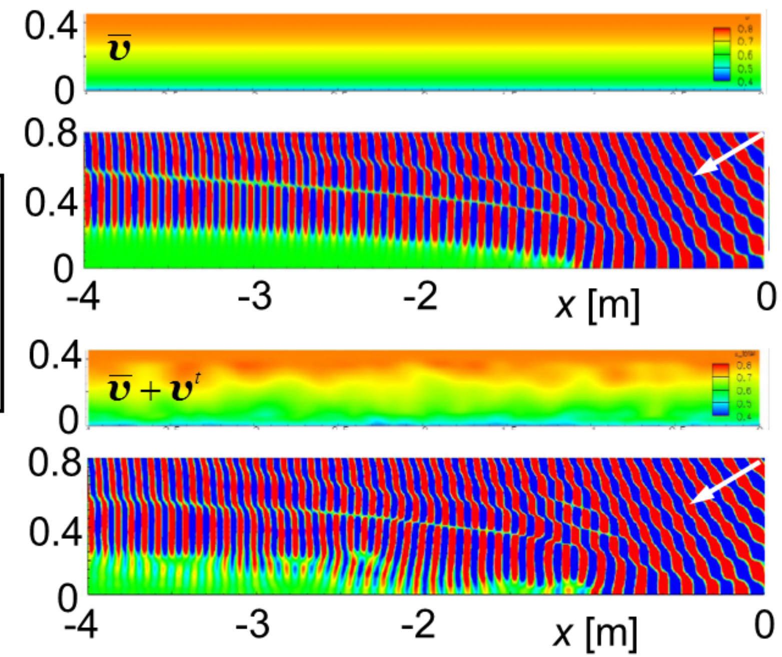
A= 3,25m x 2,8m
open/closed
V_{max}= 80/90m/s
Noise: ~ Audi-tunnel
target 2014: quietest tunnel

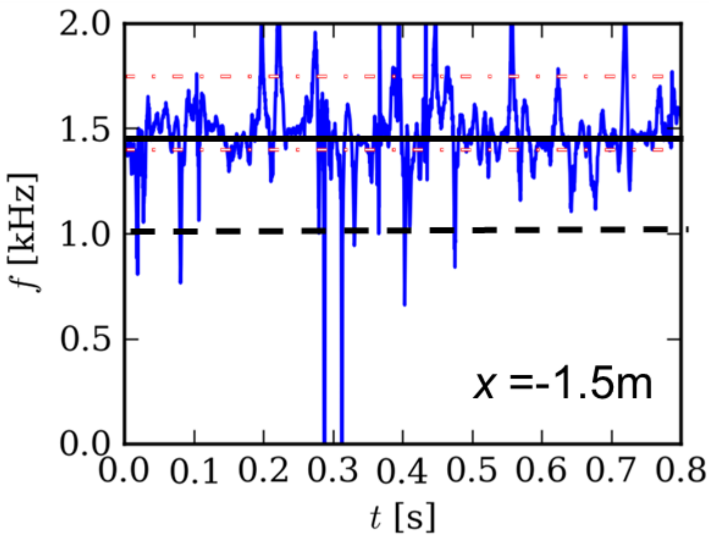
FTEG large scale acoustic wind tunnel test in DNW LLF

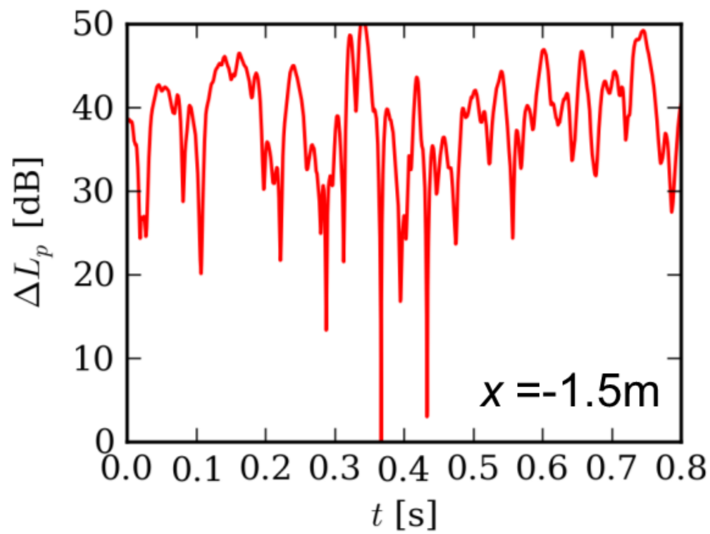
- current data not realistic for flight Re
- data needed for CAA validation



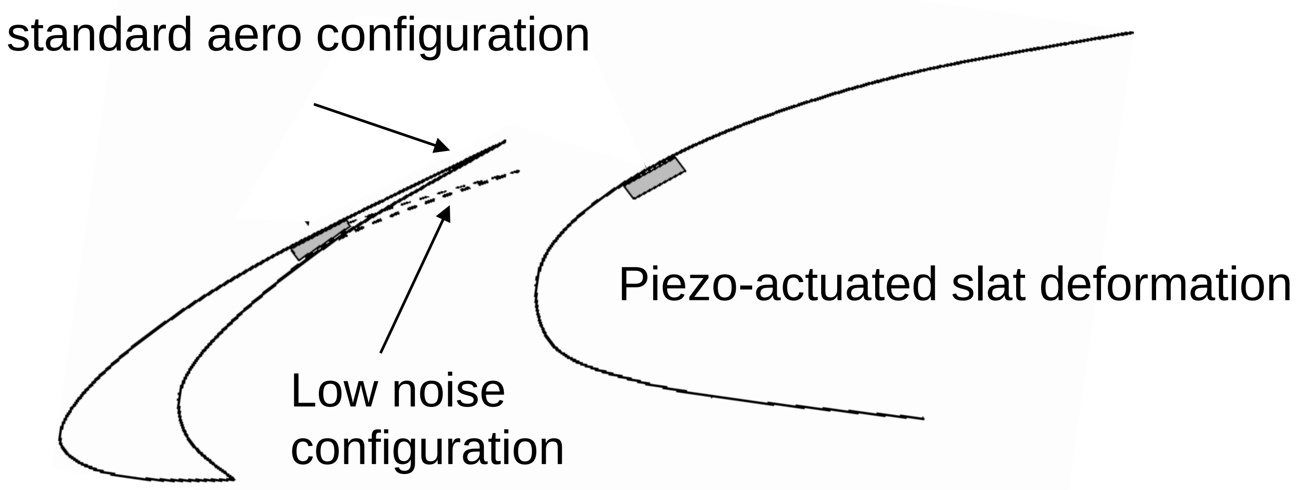

refraction
max=0.05
2 m
Refraction &
Scattering
max=2
2 m
p'
1
-1
-4
-3
-2
x [m]
0


0.4
0
$\overline{v}$
0.8
0.4
0
-4
-3
-2
x [m]
0
0.4
0
$\overline{v}+v'$
0.8
0.4
0
-4
-3
-2
x [m]
0


2.0
1.5
1.0
0.5
0.0
f [kHz]
x =-1.5m
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
t [s]


50
40
30
20
10
0
ΔL_p [dB]
x =-1.5m
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
t [s]

Adaptive reduction of slat noise



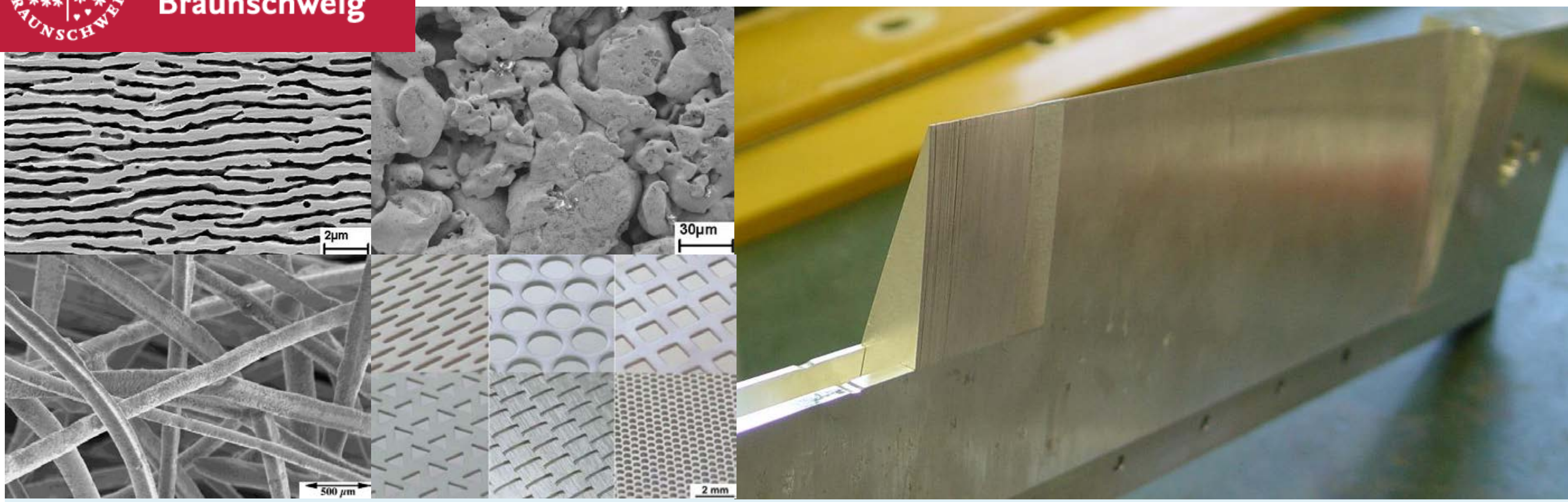
Design on the basis of CFD/CAA/CSM

EU OPENAIR
DLR SLED

Technische Universität Braunschweig

Hochauftrieb künftiger Verkehrsflugzeuge

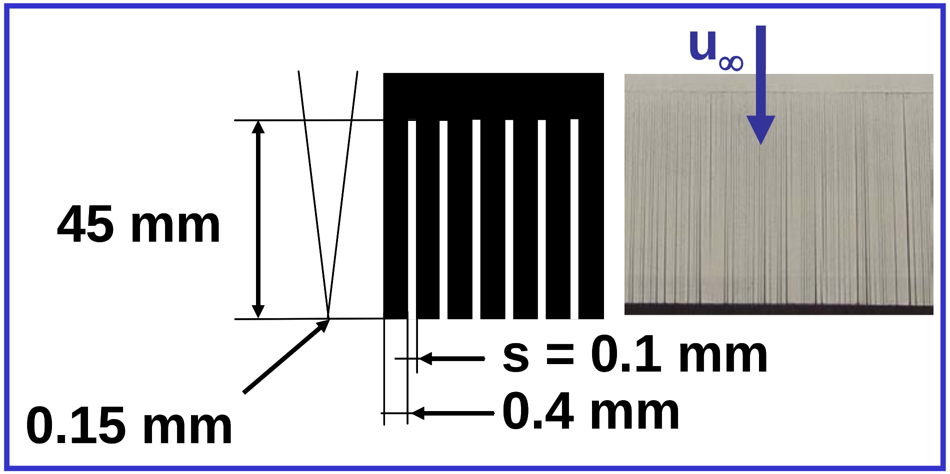
SFB 880

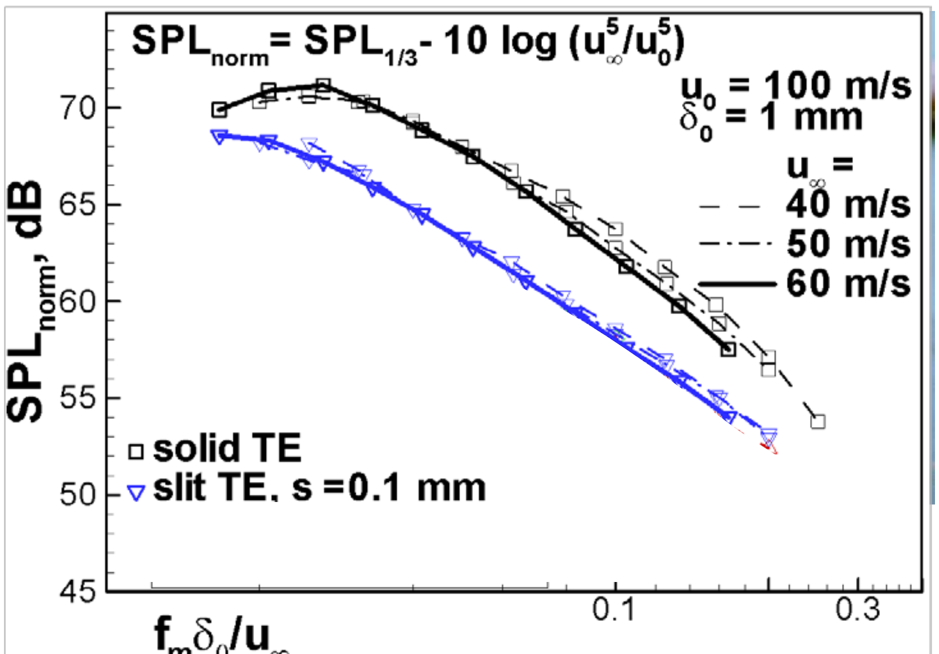


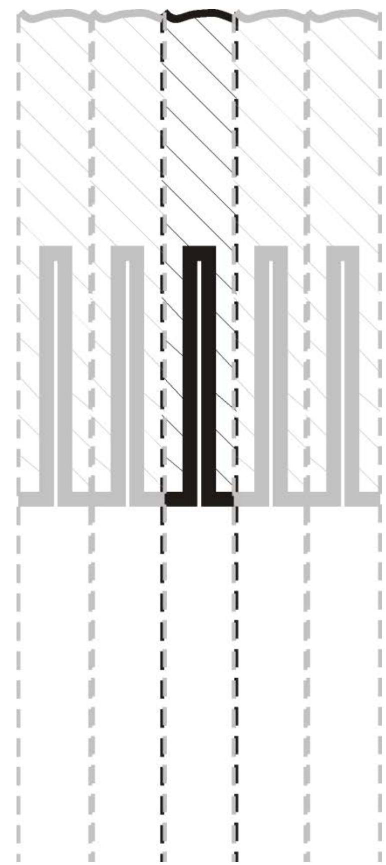
Project area A

A1: Simulation of flow noise for porous materials

Computation of noise reduction technology





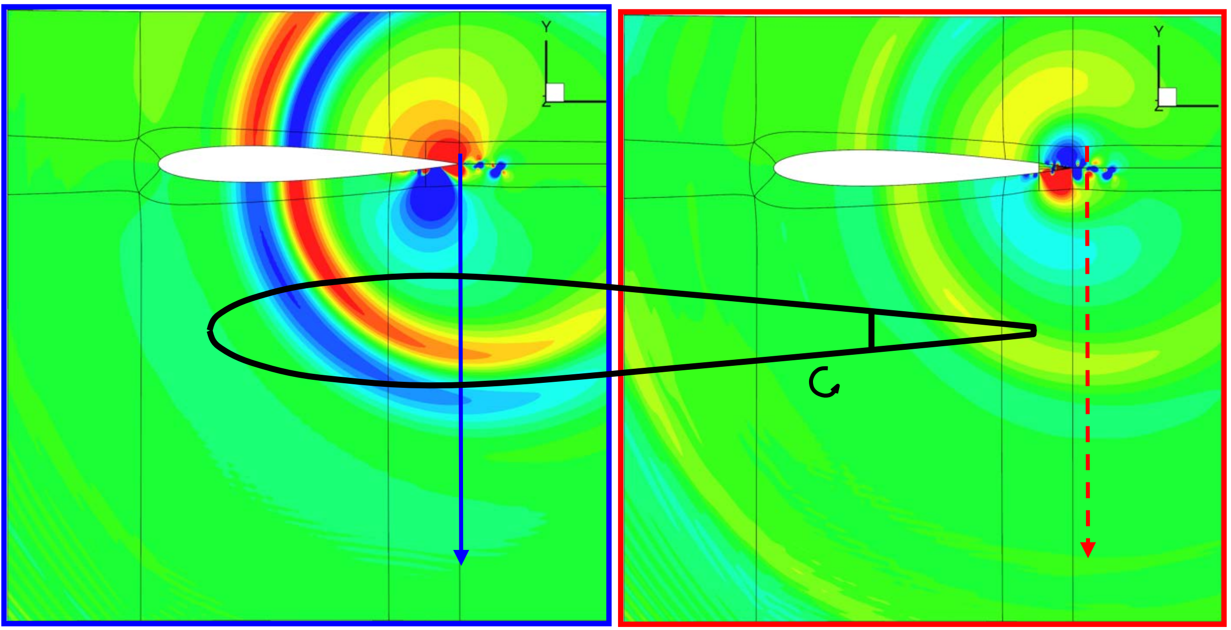


Simulation domain
spanwise periodic
8 Mpts

Hypothesis 1: change of conversion turbulence into sound

– Sound generation of test vortex passing trailing edge

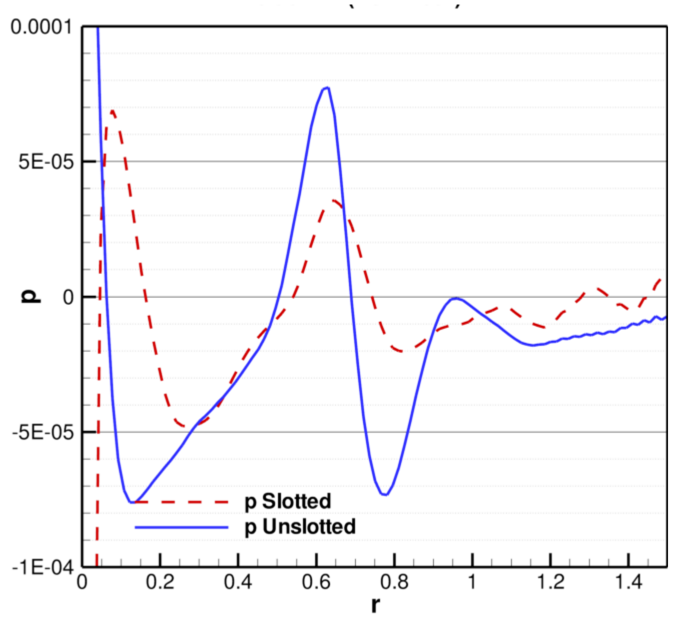
Instantaneous pressure field



unslotted

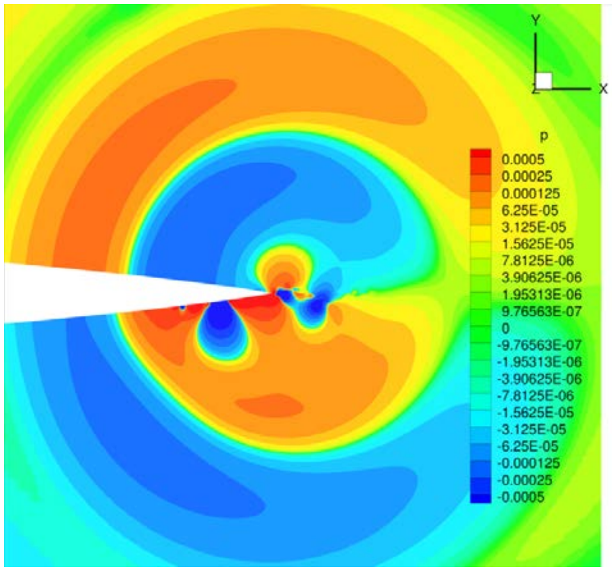
slotted

pressure profile

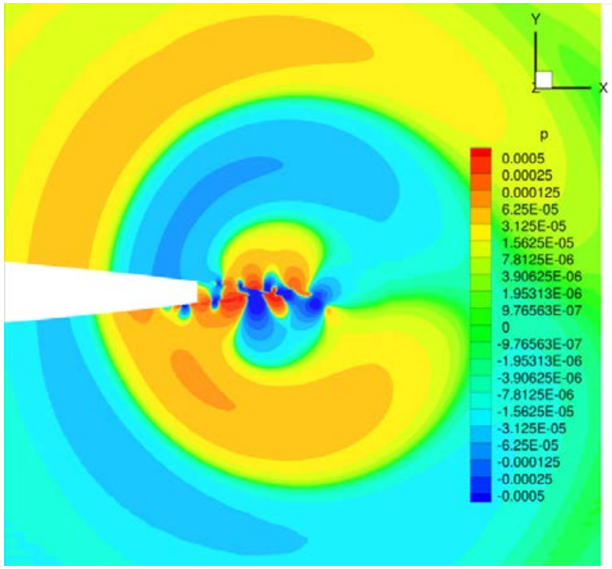


$\Rightarrow$ reduction ~ 6 dB

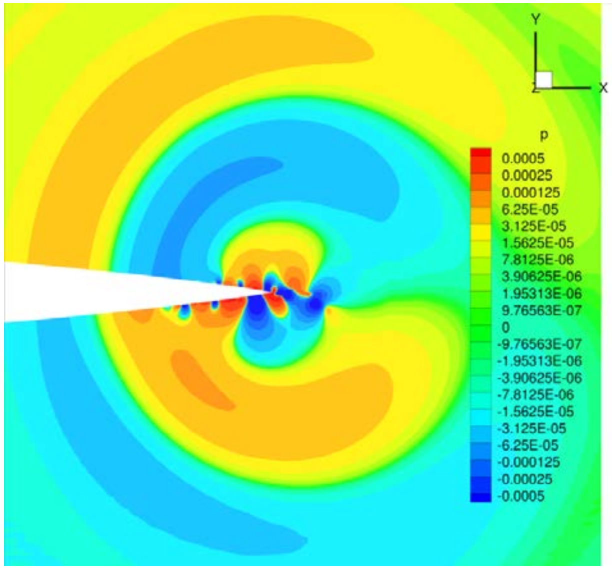
Hypothesis 1: change of conversion turbulence into sound



unslotted

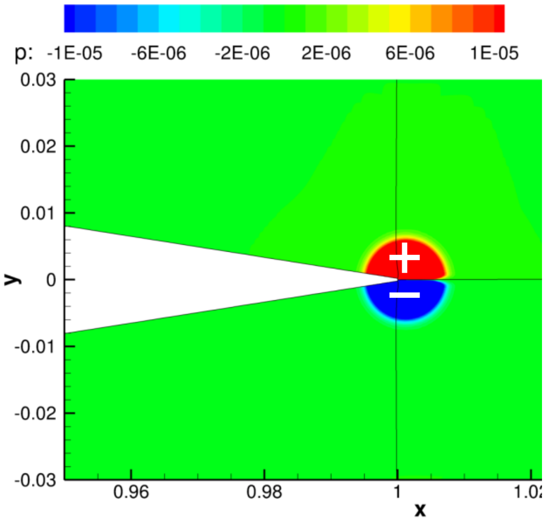


slotted (slot section)

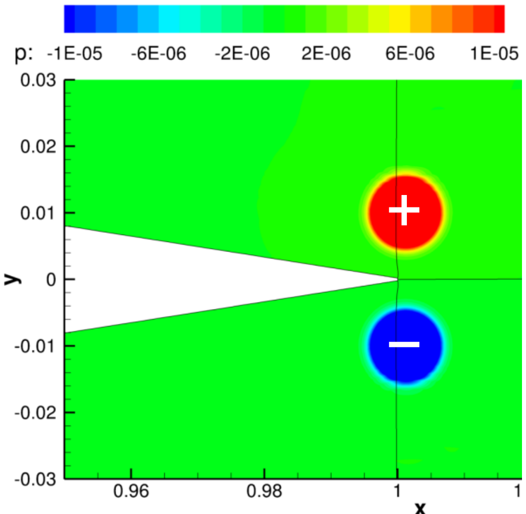


slotted (solid section)

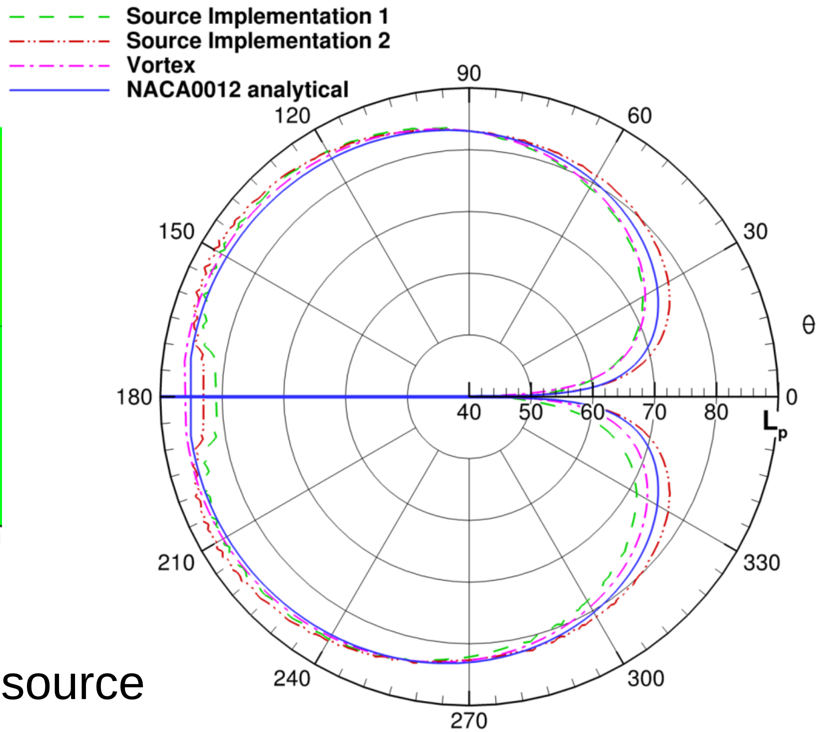
Hypothesis 2: acoustic absorption effect of slots



test source 1



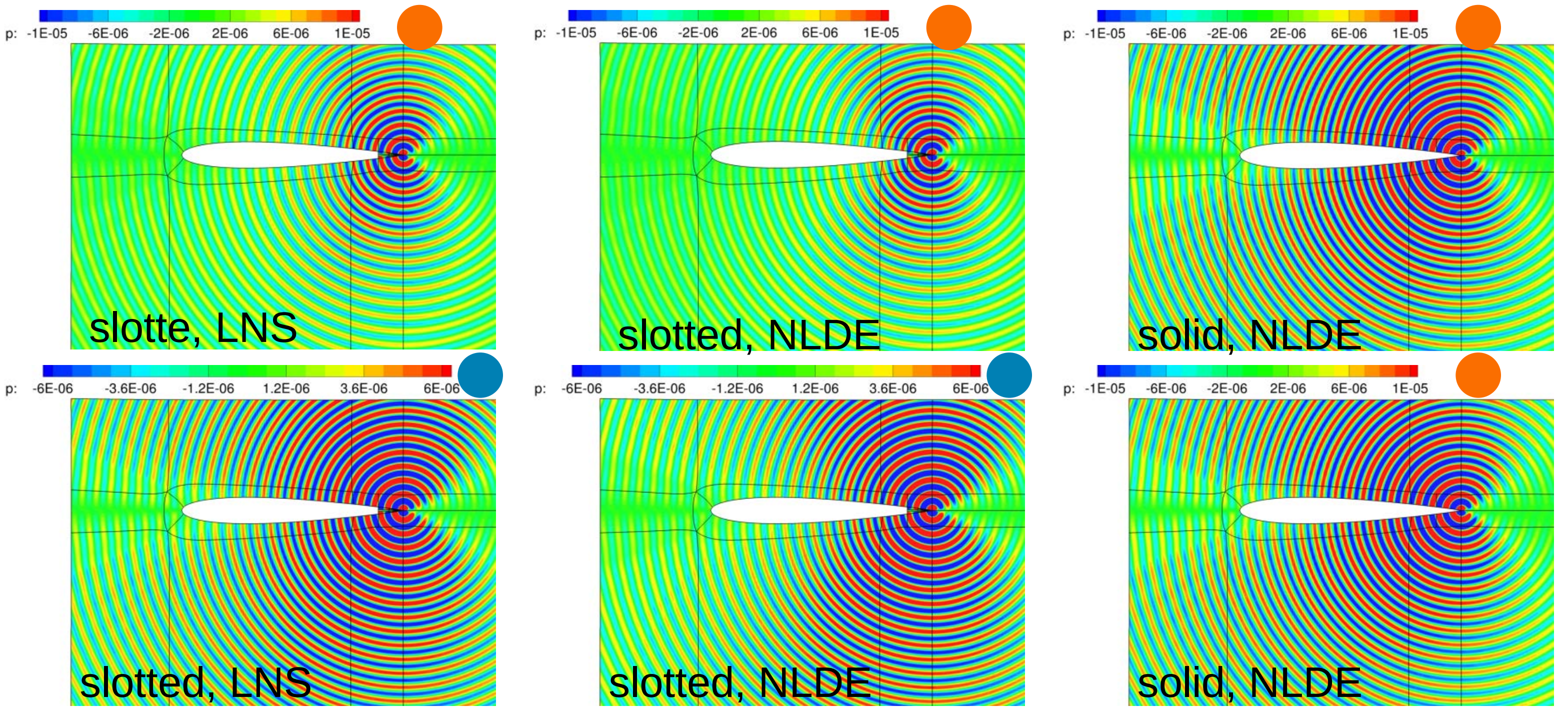
test source 2



3D-simulations with sinusoidal, cardioidic source

- Test source 1
- without viscosity influence
- with no-slip condition
- with and without mean flow

Hypothesis 2: acoustic absorption effect of slots



flow

$\pm 1 \cdot 10^{-5}$

$\pm 6 \cdot 10^{-6}$

No flow

LNS: Linearized Euler Equations with no-slip walls
NLDE: Nonlinear Disturbance equations

Reduction ~ 2dB
(probably not pure absorption effect)